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UNIVERSITÄT LÜNEBURG

SCHOOL OF PUBLIC AFFAIRS

Economics

Bachelor's Thesis

The Vaccination Game: An Analysis of Individual Vaccination Decisions incorporating Behavioral Game Theory

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May 16, 2022

Abstract

Background: Vaccination is essential for the population's protection and the complete eradication of diseases. This vaccination has a positive external effect, due to the protection of others, but the individual bears costs due to the associated risks of the vaccination. Since no excludability in the consumption of the emerging protection exists, an internal solution, i.e. a vaccination rate of less than 100%, can be assumed. Standard economic theory further suggests that this vaccination rate will always remain below herd immunity. This makes government intervention necessary. However, this view neglects behavioral and psychological research and assumes complete rationality at all times.

Method: Based on a systematic literature analysis, the question is answered which (further) factors influence the individual vaccination decision - especially with regard to bounded rationality. The results are first conceptualized for standard theory and subsequently extended to include behavioral economic and psychological literature. Based on the debate about a vaccination lottery versus compulsory vaccination in the case of Covid-19, it is discussed which concrete conclusions for state intervention can be drawn from these extensive conceptualizations.

Result: It is evident that additional influential factors exist, particularly in the individual's motivation and cognition. Standard theory disregards the significant effects of diversity in preferences, social influence, heuristics and biases (especially in the assessment of risks). These effects can be both positive and negative and are subject to considerable uncertainty. Nevertheless, it is apparent that herd immunity cannot be ruled out with voluntary vaccination.

Conclusion: In addition to compulsory vaccination, the state has other, softer methods of intervention at its disposal. In any case, these methods, as well as compulsory vaccination, require a differentiated case-by-case analysis in order to avoid possible adverse effects.

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1 Introduction

Pertussis, Rubella and now SARS-Cov-2 – vaccination has long been a central component in creating herd immunity and in effectively combating various infectious diseases. Infectious diseases not only impose enormous economic costs on society, but also endanger people's health and cause considerable suffering. With a wide, unprotected spread of these infectious diseases, the risk of mutations grows as well - as the example of Covid shows (Pachetti et al., 2020). With climate change progressing, a general increase in these infectious diseases is to be expected (McMichael et al., 2006). As a result, an increase in disease outbreaks of about five infectious diseases with pandemic potential per year has been registered (IPBES, 2020).

Due to the resulting higher risk of pandemic outbreaks, it is necessary to take a closer look at individual vaccination decisions and to derive conclusions about possible government intervention from this analysis. From the government's point of view, the goal should be to combat pandemics as cost- and time-efficiently as possible. This requires that sufficient individuals are vaccinated and herd immunity is established. These vaccinations are thereby generating both utility and cost for the vaccinated individuals in the first instance. In the second instance, however, vaccinations also generate utility for other individuals, as they will benefit from the resulting indirect protection of the vaccination as well. It remains to be clarified how exactly individuals (strategically) make this vaccination decision, which factors play a role in this decision, and which pandemic course can be expected.

From a standard economic perspective, vaccination is seen as an example of a public good from which, given individual utility maximization, a deficient provision of the same results (e.g. Buchanan, 1968; Dybvig and Spatt, 1983). According to the theory, a public good is defined in particular from its non-excludability in consumption. At the same time, since individuals are assumed to maximize only their individual utility, the smallest incurred costs of provision will already create an incentive to free-ride. Since individuals are expected to anticipate the behavior of others (see game theory; von Neumann and Morgenstern, 1944), it can be assumed for public goods that the so-called "public goods dilemma" arises, i.e., a deficit provision of them (Buchanan, 1968). In order to achieve the social optimum, government intervention is therefore imperative. Since vaccination is considered a public good, cost of vaccination exists, and individuals do not incorporate the positive externalities of vaccination into their own utility maximization, standard economic theory suggests that underprovision is likely to occur in this area as well. Game-theoretic analyses of the vaccination decision (e.g. Bauch and Earn, 2004), including epidemiological literature, as well as statistical surveys, such as the Covid related special survey of the SOEP 2020 (Graeber et al., 2021), support this hypothesis.

However, any of those analyses presuppose a complete rationality of individuals, which can be assumed to be a non-complete reflection of reality, especially with respect to bounded rationality (see Selten, 1998). Both behavioral economic and psychological research show that in everyday life deviations from the narrow concept of a purely rational/competitive homo oeconomicus exist. Other factors, such as altruism or the use of heuristics, influence daily actions and can similarly influence the individual decision to vaccinate. In order to determine the behavior of individuals in a valid way, it is necessary to identify all relevant factors, leading to the following research question:

RQ1: Which (additional) factors influence the individual vaccination decision?

The second research question arises from these identified factors:

RQ2: What factors influencing individual vaccination decisions give rise to opportunities for government intervention?

To answer these questions, a systematic literature review is conducted and conceptualized. The systematic analysis of the literature follows the method of Ogawa and Malen (1991), with the eighth step being omitted (see breakdown of the method; Randolph, 2009). After creating the initial road-map (step 1-3), the papers are classified and coded (step 4-5). This involves a scoring in which the content and the cited papers are analyzed. Depending on how appropriate the content is (scale 0-5), whether the central economic (scale 0-1) as well as behavioral economic (scale 0-1) literature has been used and whether an independent conception/empirical survey (scale 0-1) has been carried out, the respective paper is evaluated. A scoring that takes into account the journal or the number of citations is not used, as this would selectively exclude newer (working) papers. Thereafter, causal linkages are created and cross-searches are carried out (step 6). High scoring literature is identified as core literature and forms the basis for the search for contrarian findings (step 7).

The results of this literature research are presented in this thesis as follows: First, the individual vaccination decision is conceptualized from an individual utility perspective as well as based on standard economic theory. In particular, the game-theoretic analysis of Bauch and Earn (2004) is taken into account. Second, this conceptualization is expanded to possible behavioral economic factors. The basis for this extension are the three decision modes defined within the framework of the bounded rationality (Motivation, Cognition and Adaptation; Selten, 1998). Finally, based on the factors identified and the current Covid related debate on compulsory vaccination versus vaccination lottery, possible government interventions are evaluated. In this respect, the empirical papers of Kim (2021) and Graeber et al. (2021) form the foundation of the discussion.

2 Theoretical Analysis of the Vaccination Decision

Vaccinations not only benefit the vaccinated individual, they also protect other individuals and contribute to the achievement of herd immunity. However, a rationally acting individual can be expected to initially evaluate his or her own benefits and costs in this individual vaccination decision. Therefore, the individual utility analysis is elaborated in detail in section 2.1. As utility depends, in particular, on the behavior of other individuals, the next step is to determine the optimal/rational behavior by analyzing it from a game-theoretic perspective in section 2.2. The theoretical analysis is concluded in section 2.3 by incorporating behavioral economic research into game-theoretic considerations.

2.1 Individual Utility

Standard utility theory expects rational individuals - the so called agents - to act according to their preferences (Jevons, 1879; Fisher, 1892; Pareto, 1909; Hicks and Allen, 1934; Samuelson, 1938). A preference can be understood as the agent's subjective evaluation of a certain good as well as a certain situation, while a utility function represents a preference relation (Mandler, 2001). Rationality in this context implies both transitivity as well as completeness with regard to preferences (Sen, 1969), but also maximizing the agent's individual utility.

Applied to the individual vaccination decision, this agent will maximize his or her utility U_i and will, thus, choose between vaccination (U_i^V) and non-vaccination ($U_i^{\overline{V}}$). [1] These utility functions illustrate the preference relation between preferences for infection prevention (I), individual autonomy (α) and the emerging vaccination costs (c), as shown in the following equation[2]:

$$U_i^V(I^+, \alpha^{+/-}, c^-) = I_i(r_I^+, V_{-i}^-) + \alpha_i(f^+(V_{-i}^-), a^-) + c_i(r_v^-, c_V^-) \tag{2.1}$$

As indicated, vaccination will guarantee the agent positive utility by the infection prevention and disutility due to the costs incurred by the vaccination. The overall effect of the gain/restriction in individual autonomy can be both positive and negative, depending on individual preference and degree of restrictions.

In addition to individual preferences, the specific effects are dependent on several additional factors. For instance, the utility gain with respect to infection prevention (I) depends on the morbidity risk (probability of adverse consequences) of the infection (r_I) and the general vaccination level in the population (V_{-i})[3]. As the risk or

[1]For simplification purposes, the scenario of incomplete vaccination - such as the absence of booster vaccinations in the Covid pandemic - is not considered in this thesis.

[2]The positive/negative relationships shown below are to be considered inverse in the case of $U_i^{\overline{V}}$.

[3]This includes immunity as a result of an infection.

severity of adverse consequences increases, the utility gain from vaccination consequently also increases. In contrast, not only does the likelihood of infection decrease with a high level of vaccination in the population, but the individual contribution to herd immunity and, thus, indirect infection prevention decreases. The cost of vaccination (c), for its part, depends on the morbidity risk of the vaccination (r_V) and the actual cost of getting vaccinated (c_V). Hence, as the likelihood of adverse consequences of vaccination increases, the associated utility of vaccination decreases. Simultaneously, the "costs" associated with vaccination, e.g. the appointment and vaccination process and the associated expenditure of time and money, cause an additional reduction in individual utility. With regard to individual autonomy (α), a positive increase in utility can be assumed to stem from a gain in freedom due to the elimination of restrictions (f), while the encroachment of vaccination on personal liberty (a) can result in a utility decrease for some individuals. As before, the existence of restrictions (e.g. lockdowns or the AHA-L-rules[4]) is dependent on the infection incidence and, therefore, indirectly on the vaccination level.

As indicated by the indices i in equation 2.1, the influencing factors and, thus, the preferences differ on the basis of individual predeterminants. For example, Wein (2021) distinguishes between younger and older individuals in his analysis related to the Covid pandemic. It can be assumed that these groups do not only differ in terms of morbidity risk, but different levels of affectedness due to a lockdown in combination with a different need for freedom may additionally exist.

Despite these predeterminants and regardless of whether cardinal or ordinal utility is assumed, initial deductions regarding a possible vaccination behavior can be drawn from this individual utility analysis. Taking into account ordinal utility theory (like Fisher, 1892; Pareto, 1909; Hicks and Allen, 1934), it is possible, for instance, for the agent to value the gain in utility from protection against infection higher than the costs incurred from vaccination. Furthermore, comparing the scenario with a low vaccination level in the population to a high one, it can be seen that the benefit of vaccination in the scenario with a notably lower vaccination coverage is *c.p.* higher or at least equal. This implies

$$U_i^V(V_{-i} = \text{low}) \geq U_i^V(V_{-i} = \text{high}). \tag{2.2}$$

In the case of herd immunity (HI), the following relationship is obtained:

$$U_i^V \leq U_i^{\overline{V}} \quad \text{if} \quad V_{-i} = HI \tag{2.3}$$

[4]The AHA-L-rules were established in Germany during the Covid pandemic and include maintaining distance, adhering to hygiene measures, wearing masks, and ventilating regularly. These rules are associated with a restriction of social interactions as well as monetary costs, resulting in disutility for individuals.

This coincides with the analysis under consideration of (hedonistic) cardinal utility theory (Jevons, 1879; Ramsey, 1926; von Neumann and Morgenstern, 1944), since

$$\frac{\partial U_i^V}{\partial V_{-i}} < 0 \tag{2.4}$$

holds, as long as herd immunity is not reached. Given the negative marginal utility, if V_{-i} converges against herd immunity (HI), then

$$\lim_{V_{-i} \to HI} U_i^V(I, \alpha, c) = 0 + \alpha_i^- + c_i^- < 0 \tag{2.5}$$

will hold, which implies

$$\overline{V} \succeq V \quad \text{iff} \quad U_i^{\overline{V}} \geq U_i^V. \tag{2.6}$$

Thus, a rational agent will, at some point, depending on individual predeterminants and the disutility that may arise, prefer the non-vaccination option. The agent's individual threshold is reached - with the exception of an instantaneously fatal infection and, hence, a utility gain from infection prevention near infinity - in any case before obtaining herd immunity.

Even in this highly simplified view, where the agent can decide to vaccinate at a given time depending on the level of vaccination in the population, it is evident that the optimal amount of provision of the public good will not be provided (figure 2.1).

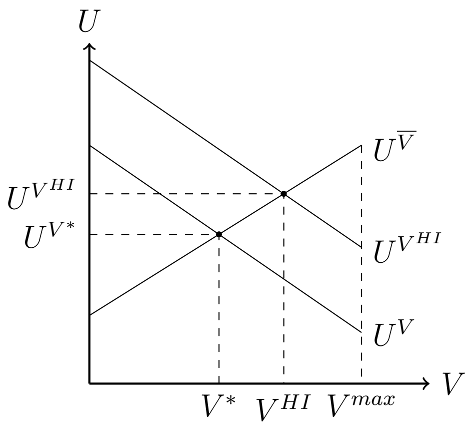

Figure 2.1: Aggregated individual vaccination decisions versus the social optimum

(Source: Own visualization, based on Wein (2021) and, therefore, indirectly on Francis (1997))

The previous remarks would imply that the social optimum would consequently not be achieved. Contrary to e.g. Wein (2021), the societal optimum is understood to be herd immunity, partly because of the long-term economic costs of incomplete eradication of a vaccine-preventable disease (Eichenbaum et al., 2021; Acemoglu et al., 2021) and the possibility of a recurrence triggered by a possible mutation (Pachetti et al., 2020). Since this social optimum would not be achieved based on current assumptions, government intervention would be essential. This government intervention could, on the one hand, increase the utility of vaccination (U^V), but on the other hand, increase the disutility of not vaccinating ($U^{\overline{V}}$).

However, previous considerations are biased as one agent's behavior affects the behavior of other agents and choices are made in the presence of uncertainty. All agents deal with this uncertainty by including the ex-ante perceived risks in their individual expected utility calculations (von Neumann and Morgenstern, 1953). At the same time, the behavior of other agents, so-called players, are also taken into account in the agent's maximization of utility in this vaccination game. This inclusion leads to each player forming a best response with respect to the behavior of other players. As the best response of the players depends on the behavior of the other players, each player has a extensive strategy set at his or her disposal. In order to check whether the previous simplified explanations are validated by taking into account the behavior of other individuals, a game-theoretical analysis is carried out in the following.

2.2 Game Theory

> "Game theory can be defined as the study [...] of conflict and cooperation between intelligent rational decision makers. [...] A decision maker is rational if he [or she] makes decisions consistently in pursuit of his [or her] own objectives." (Myerson, 1997, p.1)

As this general definition suggests, individuals facing the vaccination decision are confronted with the choice between conflict and cooperation. By individuals cooperating, herd immunity and, thus, the social optimum can be achieved. However, this cooperation conflicts with the fact that not every individual is needed to achieve herd immunity as well as with the absence of excludability in the consumption of infection prevention. Therefore, there are sufficient incentives for individuals to free-ride, which, however, indirectly influences the willingness to cooperate. This relationship is illustrated from the perspective of the individual in table 2.1. It can be seen that the payoff is highest when the individual does not get vaccinated while all others do, and, hence, the cost of vaccination can be avoided with simultaneous infection prevention.

The individual's payoff in this case can be understood as an expected utility, since it is determined by the risk of infection ($\pi_{V_{-i}}$):

$$EU_i = \pi_{V_{-i}} U^{Infection} + (1 - \pi_{V_{-i}}) U^{non-Infection} \tag{2.7}$$

		Other individuals $-i$: V	Other individuals $-i$: $\overline{V}$
Individual i	V	$EU_i = 8$	$EU_i = 5$
	$\overline{V}$	$EU_i = 10$	$EU_i = -1$

Table 2.1: Individual payoff of a vaccination given the behavior of other individuals

(Source: Own illustration with arbitrary numbers assuming previous considerations from section 2.1, indirectly based on Wein (2021))

The individual utility functions depend on the vaccination decision as well as the other determinants mentioned in the previous section, such as the morbidity risk of the vaccination (r_V) or infection (r_I).

Continuing these initial executions of a sequential ex-post decision in a still simplified simultaneous two-player game yields the payoff matrix shown in table 2.2. It is apparent that no dominant strategy exists for either player. This implies that both the vaccination and non-vaccination options may be rational in different situations.

		Individual j: V	Individual j: $\overline{V}$
Individual i	V	$(8, 8)$	$\underline{5}, \underline{10}$
	$\overline{V}$	$(\underline{10}, \underline{5})$	$(-1, -1)$

Table 2.2: Payoff matrix in a simultaneous two player game

(Source: Own illustration with in its value arbitrary numbers)

It can additionally be seen that two Nash equilibria exist in pure strategies (PSNE), which are outcomes in which neither player has an incentive to deviate (Nash, 1951):

$$PSNE = \{(V, \overline{V}), (\overline{V}, V)\} \tag{2.8}$$

This set of strategy profiles implies that it is rational to get vaccinated, assuming that the other player will not get vaccinated and vica verse. Neither player has an incentive to deviate given the other player's behavior, as otherwise he or she would be worse off. Given the uncertainty about the other player's behavior, it is rational for each of the players to randomize between their strategies. These mixed strategies lead to a corresponding mixed strategy equilibrium (MSNE)

$$MSNE = ((\frac{3}{4}, \frac{1}{4}), (\frac{3}{4}, \frac{1}{4})), \tag{2.9}$$

whereas the first value in each case represents the probability of performing the strategy vaccination (P). Extrapolating these results from 2 to n identical players, suggests that 75% would get vaccinated.

However, since this consideration is based on the utils arbitrarily assigned in the value, the more general analysis of Bauch and Earn (2004) is presented hereafter.[5] In particular, this allows to incorporate that, as the infection probabilities change due to a rise in the general vaccination level (V_{-i}), the expected payoff is constantly adjusting and cannot be considered rigid as in the previous model. Following the authors, the expected payoff of the player in this strategic decision is defined as

$$EU_i(P, V_{-i}) = P(-r_V) + (1 - P)(-r_I \pi_{V_{-i}}), \tag{2.10}$$

which can be rewritten by establishing a relative risk ($r = r_V/r_I$) to

$$EU_i(P, V_{-i}) = -rP - \pi_{V_{-i}}(1 - P). \tag{2.11}$$

The authors further argue that the vaccination level is based on the decision between a hypothetical strategy P and Q

$$V_{-i} = \varepsilon P + (1 - \varepsilon)Q, \tag{2.12}$$

whereas ε is a proportion of the population that vaccinates with probability P and $1 - \varepsilon$ with probability Q. This implies not only individual payoffs for individuals playing P of

$$EU_P(P, Q, \varepsilon) = EU_i(P, \varepsilon P + (1 - \varepsilon)Q) \tag{2.13}$$

and for individuals playing Q of

$$EU_Q(P, Q, \varepsilon) = EU_i(Q, \varepsilon P + (1 - \varepsilon)Q) \tag{2.14}$$

but at the same time a payoff gain to an individual playing P of

$$\Delta EU = EU_P - EU_Q = [\pi_{-rP - \pi_{V_{-i}}(1-P)} - r](P - Q). \tag{2.15}$$

If a large portion of the population adapts strategy P and that leads to higher payoffs than strategy Q, there is no incentive for them to deviate from their strategy. In this case, strategy P represents a Nash Equilibrium. Moreover, if individuals choose a strategy that is closer than Q to P and, therefore, receive a higher payoff than Q, the Nash equilibrium is convergently stable (Bauch and Earn, 2004). The authors illustrate that the payoff gain ΔEU is understood as an incentive for individuals to adopt from strategy Q to P and that, hence, at any given relative risk a unique strategy $P = P^*$ exists. Consequently, after Bauch and Earn (2004), the result is a

[5] All equations taken from other elaborations have been changed with respect to the notation to be consistent within this thesis. There is no change in the substance of the content.

unique pure strategy convergently stable Nash equilibrium (PSCSNE)

$$PSCSNE = \{(P^*, P^*)\} \quad \text{with} \quad P^* = 0 = \overline{V} \quad \text{iff} \quad r \geq \pi_0 \tag{2.16}$$

as well as a mixed strategy convergently stable Nash equilibrium (MSCSNE)

$$MSCSNE = ((P^*, 1 - P^*), (P^*, 1 - P^*)) \quad \text{with} \quad 0 < P^* < 1 \quad \text{iff} \quad r < \pi_0. \tag{2.17}$$

This PSCSNE implies that in case of a sufficiently risky vaccine ($r \geq \pi_0$) every player will choose strategy $P^* = 0$, which is to not vaccinate. However, if and only if $r < \pi_0$ applies, every player will vaccinate with the nonzero probability P^*, depending on the relative risk (Bauch and Earn, 2004). As this MSCSNE and, thus, the concrete probability P^* are dependent on the infection probability ($\pi_{V_{-i}}$), the authors implement the SIR Model into the game-theoretic considerations.

The SIR model is an epidemiological model, initially introduced by Kermack and McKendrick (1927), that is implemented both for the direct estimation of infectious diseases and in particular childhood diseases (e.g. Anderson and May, 1992; Stone et al., 2000; Bjørnstad et al., 2002), but also by economists for the estimation of associated economic outcomes (e.g. Acemoglu et al., 2021; Eichenbaum et al., 2021; Jones et al., 2021; McAdams, 2020; Farboodi et al., 2020; Alvarez et al., 2020). While individual secondary parameters may differ between models, the three-component SIR model divides the individuals into three epidemiological states: "susceptible" (S), "infected" (I) and "recovered" (R). At any given time t, each individual is assignable to one of the epidemiological states ($S + I + R = 1$). Consequently, the general distribution of those epidemiological states and the associated rates of change can be used to model epidemics.

Fundamental in the subsequent game-theoretic calculations of Bauch and Earn (2004) are the reproduction rate $\mathcal{R}_0$ and the parameter f. The reproduction rate, which is defined by Bauch and Earn (2004) as "the average number of secondary cases produced by a typical primary case in a fully susceptible population" (p. 13392), is determined by the mean transmission rate (β), the mean birth and death rate (μ) and the mean infectious period ($1/\gamma$)

$$\mathcal{R}_0 = \frac{\beta}{\gamma + \mu}, \tag{2.18}$$

while f is the proportion of the infection period and the mean lifetime

$$f = \frac{\mu}{\gamma}. \tag{2.19}$$

The authors indicate that herd immunity is dependent on the reproduction rate

$$V^{HI} = \begin{cases} 0 & \text{if} \quad \mathcal{R}_0 \leq 1 \\ 1 - \dfrac{1}{\mathcal{R}_0} & \text{if} \quad \mathcal{R}_0 > 1 \end{cases}, \tag{2.20}$$

which implies that as long as $V_{-i} \geq V^{HI}$ holds, a disease free state $(\hat{S}, \hat{I}) = (1 - V_{-i}, 0)$ will be achieved. However, if herd immunity is not achieved, it converges to an endemic state with

$$\hat{S} = 1 - V^{HI} \tag{2.21}$$

and

$$\hat{I} = \frac{f}{1+f}(V^{HI} - V_{-i}). \tag{2.22}$$

According to Bauch and Earn (2004), it follows that the risk of infection ($\pi_{V_{-i}}$) can be described as

$$\pi_{V_{-i}} = 1 - \frac{1}{\mathcal{R}_0(1 - V_{-i})}, \tag{2.23}$$

indirectly resulting in the MSCSNE P* (compare equation 2.17; see appendix B for a detailed derivation)

$$P^* = 1 - \frac{1}{\mathcal{R}_0(1 - r)}, \tag{2.24}$$

which is the probability that each player plays the strategy vaccination. Additionally, since this equilibrium is convergently stable, it is to be expected that this is likely to be observable in a real population (Eshel, 1996). In conjunction with equation 2.20, it can be seen that for any relative risk $r > 0$, herd immunity (V^{HI}) is not achieved (see figure 2.2).

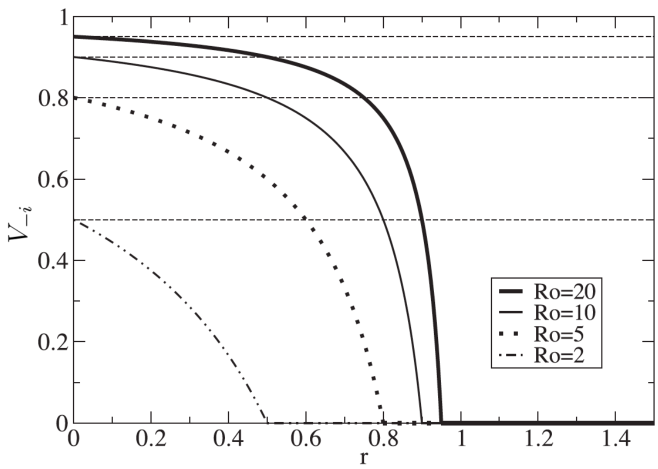

Figure 2.2: Vaccine coverage V_i at the MSCSNE versus the relative risk r

The vaccine level in the population that can be expected based on the vaccination probability P^* for various values of the reproduction rate $\mathcal{R}_0$ (see equation 2.24). The horizontal lines indicate the critical level of vaccine coverage to reach herd immunity V^{HI} (see equation 2.20).

(Source: Bauch and Earn (2004))

The model calculations of Bauch and Earn (2004) are, thus, consistent with the previous simplified explanations and the general economic theory regarding the provision of public goods (Buchanan, 1968; Dybvig and Spatt, 1983). Any risk (or as in section 2.1 introduced: cost c) associated with the vaccination will lead to to a scenario in which it is no longer rational to be vaccinated. Since this scenario is reached before herd immunity, it will not lead to an optimal provision of the public good and, hence, no complete eradication of the disease on a voluntary basis. The resulting need for state intervention is consistent with both previous qualitative explanations (e.g. Geoffard and Philipson, 1997; May, 2000) and other game-theoretic simulations (e.g. Barrett, 2003; Galvani et al., 2007; Laguzet and Turinici, 2015; Alam et al., 2019).

Nevertheless, this game-theoretic simulation based on the SIR model is subject to a number of limitations, so its transferability cannot be guaranteed without restrictions. First, the SIR model assumes the presence of only three states. Additional states can be, for example, "asymptotic but contagious" (Alvarez et al., 2020). Consequently, not only are there a number of additional epidemiological models, such as SIR, SIER, SIS, SAIRS or SIQR, but these so called compartment models also differ from further stochastic and deterministic models (Huang and Zhu, 2022; as illustrated in appendix C). By including other epidemiological models into the game-theoretic simulations, other decisions of individuals can, as a result, be anticipated. At the same time, Bauch and Earn (2004) assume the presence of complete vaccination protection and the absence of incomplete vaccinations (e.g. only one of two doses). However, as these influencing factors depend on the specific disease, the use of the general model is nevertheless suitable for an initial evaluation, especially since the addition of reinfections, for example, would not change the results positively.

In addition, the game-theoretical analysis itself is based on further assumptions that can be considered critically. For instance, it has to be assumed that all individuals have access to the same information and process this information in the same way. In particular, risk perception variance and further effects of risk perception spreading non-homogeneously through social networks were not considered (Bauch and Earn, 2004). This implies that the risks r_V, r_I and, thus, r implemented in the previous considerations should only be understood as perceived risks. Yet, the rational management of these perceived risks implies, as indicated in the opening quotation by Myerson (1997), *intelligent rational decision makers*.

It is questionable how this intelligent rationality is to be understood. Throughout the foregoing, it is assumed that the individual maximizes his or her individual utility rather than the utility of the society as a whole. This behavior as a *homo oeconomicus* is thereby classified as the rational behavior. The correct inclusion of information about, for example, the behavior of other individuals and possible risks is considered to be intelligent. However, the categorization as a homo oeconomicus raises the further question of whether he or she is an egoistic, altruistic or utilitarian homo oeconomicus. It may be rational for some individuals to behave selfishly, while for others it is rational to act for the good of the group. For example, the inclusion of altruistic preferences in previous game-theoretic reasoning shows that an outcome closer to the social optimum would be obtained (Shim et al., 2012). Meanwhile, it also may be perfectly rational for individuals to choose the strategy V from a set of strategies $\{V, \overline{V}\}$ in certain situations, no matter that $\overline{V} \succeq V$ holds (analogous to the generic explanations by Mandler, 2001). Furthermore, it is questionable whether individuals are able to cognitively process the complex information and therefore to act intelligently. Mental shortcuts, the existence of biases in cognitive processing or the simple presence of insufficient statistical knowledge cast doubt on the "intelligence" of the decision makers. In the following section, exactly these behaviorally economic (cognitive) factors of influence, which possibly have an impact on the vaccination decision of the individuals, are elaborated on.

2.3 Behavioral Game Theory

As Selten (1998) has recognized, "[h]uman economic behaviour [sic] has a complex structure" (p. 414). The behavior anticipated by the neoclassically dominated homo oeconomicus differs from the behavior which is actually observed in real world setting. Precisely this "rationality exhibited by actual human economic behaviour [sic]" is understood hereby, in reference to Simon (1957), as *bounded rationality* (Selten, 1998, p. 413). This bounded rationality is attributable, among other things, to the fact that individuals make decisions under risk, time pressure, incomplete information and with limited mental capacities. This is resulting in the decisions individuals are making being shaped by heuristics (Tversky and Kahneman, 1974) and mental accounting (Thaler, 1985). These heuristics partly yield unreasonable outcomes, e.g. caused by overconfidence, optimism or the wrong estimation of probabilities (Kahneman et al., 1982). In these decision-making processes, according to Selten (1998), three different mental processes are present:

1. *Motivation* - the driving force.

2. *Cognition* - reasoning.

3. *Adaptation* - routine adjustment without reasoning.

Given that it can be assumed that these mental processes are also involved in the decision to vaccinate, the following section uses these three mental processes to analyze how the previous game-theoretic analysis could be extended.

However, in the following, the behavioral economic aspects are not seen as necessarily contradictory to the neoclassical rationality of the homo oeconomicus. Instead, they are perceived as an extension of the latter. It may, for example, be rational for an individual, who first of all maximizes his or her utility, to behave altruistically, if this increases his or her individual utility. Moreover, seemingly unreasonable outcomes due to mental shortcuts can also be understood as rational and intelligent, since a complete processing of all available information would not only result in directly related disutility, it is in most of the cases also merely not possible. It is intended to adequately represent the heterogeneity of diverse rational and intelligent decision-makers in the society and to extract information from this heterogeneity.

2.3.1 Motivation

Motivation in the sense of Selten (1998) is defined as the actual goal of the individuals' actions and how these goals, desires and fears translate into concrete action. In specific terms, this can be understood as the trade-off between benefits and costs, which has already been presented in sections 2.1 and 2.2. The agent maximizes his or her individual utility and chooses the option/strategy that brings him or her the highest expected utility/payoff. In contrast to the previous consideration, the diversity in terms of preferences, due to different types of individuals or different social influences, will be examined in more detail.

2.3.1.1 Diverse Preferences: Altruists, Egoists and Hooligans

So far, it has been strictly assumed that in the vaccination game only one type of player exists, even though this does not reflect the existing diversity of society. Not only do players enter the game with a different motivation due to pre-existing diversity, but it can also be assumed that depending on the domain and the other players, preferences may change (Levine, 1998; Falk and Fischbacher, 2006). In principle, a number of preferences in various degrees are possible: egoistic, spiteful, utilitarian, altruistic and rawlsian preferences.[6] Consequently, three types of players are assumed in the following: the egoist, the altruist and the hooligan.

The egoist conforms to the classical understanding of the homo oeconomicus, who maximizes his or her own utility, which is not dependent on other individuals. This results in the utility function U_i^V shown in equation 2.1 and the payoff matrix given in table 2.1.

The altruist, in contrast, includes other individuals in his or her individual utility maximization. Since in the case of vaccination, altruistic, utilitarian and also rawl-

[6] This is not intended to be exhaustive and, for simplicity, excludes important contributions such as the inequality aversion introduced by Fehr and Schmidt (1999)/Bolton and Ockenfels (2000).

sian preferences benefit from herd immunity and, hence, the protection of others, these are summarized as the altruist player type. Nevertheless, these preferences are not generally to be used synonymously, as shown below. Altruistic preferences induce the inclusion of the utility of others, with a certain discount, in one's own utility maximization calculus (Fehr and Schmidt, 2006):

$$U_a^V = \alpha U_i^V + \beta U_{-i}^V \tag{2.25}$$

However, this benefit from the well-being of others is to be understood as unconditional (Andreoni, 1989; Andreoni and Miller, 2002) and, hence, as distinct from reciprocal behavior (Levine, 1998; Fehr and Schmidt, 2006; Segal and Sobel, 2007). In addition, a behavior is considered altruistic even if it is not necessarily accompanied by the abandonment of fitness in the evolutionary biological sense (Eshel et al., 1998). Thus, the inclusion of others in one's own utility maximization, even if no visibly altruistic behavior follows from it, is sufficient to be considered altruistic. In this broad definition of altruism, utilitarian and rawlsian preferences can also be added, since utilitarian preferences imply maximizing the overall social benefit

$$U_u^V = U_i^V + U_{-i}^V, \tag{2.26}$$

while rawlsian preferences favor the option where the welfare of the weaker is maximized

$$U_r^V = min\{U_i^V, U_{-i}^V\}. \tag{2.27}$$

Nevertheless, all three preferences are unified by the fact that the marginal utility is (in certain cases) positive with respect to the utility of others. Thus, in an ex ante consideration, it cannot necessarily be said, as previously shown in equation 2.5, that herd immunity is not achievable.

The hooligan is defined as an individual who profits from causing harm to others (Eshel et al., 1998). This can be caused by either spitefulness, and hence benefiting from the disutility of others, or by envy, and hence the disutility that arises when others are doing well (Levine, 1998; Balafoutas et al., 2012). This associated utility function can therefore be described as

$$U_h^V = \alpha U_i^V - \beta U_{-i}^V, \tag{2.28}$$

whereas the marginal utility derived from the utility of others is negative.

While it is reasonable to assume that in a hypothetical world full of hooligans, herd immunity would not be achieved, it can be assumed that it would be achieved in the case of exclusively altruistic players - especially when altruism makes the strategy vaccination dominant. However, since in reality all three types of players are present and have at least basic knowledge about the presence of the other types, it is again required to anticipate their behavior using game theory.

Reconsidering the very simplistic two-player vaccination game (see section 2.2), in this case with one egoistic and one altruistic player ($\alpha = 4/5; \beta = 1/5$), yields the payoff matrix shown in table 2.3. While the PSNE does not change, the new MSNE $= ((3/4, 1/4), (7/8, 1/8))$ is obtained. This implies that, in equilibrium, the egoist is 75% likely to vaccinate and the altruist is 87.5% likely to vaccinate. Transferring this to n individuals under the assumption of a 50/50 distribution results in a vaccination rate of 81.25% (increase of 6.25 pp compared to equation 2.9).

		Altruist j	
		V	$\overline{V}$
Egoist i	V	$(8, 8)$	$(\underline{5}, \mathbf{9})$
	$\overline{V}$	$(\underline{10}, \mathbf{6})$	$(-1, -1)$

Table 2.3: Payoff matrix in a simultaneous two player game - altruist ($\alpha = 4/5; \beta = 1/5$) versus egoist

(Source: Own illustration with in its value arbitrary numbers (overview in appendix B); value changes through altruism are highlighted bold)

However, table 2.4 shows that the level of vaccination does not necessarily increase with increasing altruism. As strategy vaccination becomes dominant for the altruist, the egoist anticipates this, which encourages him or her to ride free. This leads to the unique PSNE $= \{(\overline{V}, V)\}$.

The same relationship can be seen in its inverse form, if the game would consist of only one egoist and one hooligan. For a low-grade distinct hooligan ($\alpha = 4/5; \beta = 1/5$), this would imply again no changes in the PSNE and a new MSNE $\approx ((3/4, 1/4), (5.4/10, 4.6/10))$. In the case of the high-grade hooligan ($\alpha = 2/5; \beta = 3/5$), it yields the new unique PSNE $= \{(V, \overline{V})\}$. This indicates that only 50% would get vaccinated, which is exactly the same result as for the egoist and the high-grade altruist.

		Altruist j	
		V	$\overline{V}$
Egoist i	V	$(8, \underline{8})$	$(\underline{5}, \mathbf{7})$
	$\overline{V}$	$(\underline{10}, \underline{\mathbf{8}})$	$(-1, -1)$

Table 2.4: Payoff matrix in a simultaneous two player game - altruist ($\alpha = 2/5; \beta = 3/5$) versus egoist

(Source: Own illustration with in its value arbitrary numbers (overview in appendix B); value changes through altruism are highlighted bold)

In reality, however, the vaccination game does not consist of only two types of players, but all three of them play simultaneously. This produces the following, again highly simplified, simultaneous three player game[7]:

Hooligan k plays V		Altruist j: V	Altruist j: $\overline{V}$
Egoist i	V	$(8, 8, 4.8)$	$(\underline{8}, \underline{9.6}, \underline{4.64})$
	$\overline{V}$	$(\underline{10}, \underline{8.4}, \underline{4.56})$	$(5, 5, \underline{3.8})$

Hooligan k plays $\overline{V}$		Altruist j: V	Altruist j: $\overline{V}$
Egoist i	V	$(\underline{8}, \underline{8}, \underline{6.4})$	$(\underline{6}, 5.2, 2.88)$
	$\overline{V}$	$(5, \underline{5.8}, 2.92)$	$(-1, -1, -0.6)$

Table 2.5: Payoff matrix in a simultaneous three player game - altruist ($\alpha = 4/5; \beta = 1/5$) versus egoist versus hooligan ($\alpha = 4/5; \beta = 1/5$)

(Source: Own illustration with in its value arbitrary numbers (appendix B))

As no strictly dominant strategy exists, all strategies must be used by the players, resulting in the PSNE $= \{(V, \overline{V}, V), (V, V, \overline{V}), (\overline{V}, V, V)\}$ and the MSNE $\approx ((39/50, 11/50), (44/50, 6/50), (37/50, 13/50))$. Extrapolating the exact MSNE results to n individuals, assuming an equal distribution of the player types, yields a vaccination level of 79.13%.

Nonetheless, in reality, it cannot usually be assumed that these player types are equally distributed. Instead, through experiments conducted with the so-called dictator game, the player's pure preference can be revealed, since only a one-sided relationship and, therefore, no interaction in terms of reciprocity exists. Using a large number of these dictator games, where an individual is allocated a sum of money and decides how much of it another individual gets, Andreoni and Miller (2002) show that on average almost 50% of the individuals have pure egoistic preferences, which means keeping all the money, and 50% altruistic preferences in varying degrees of intensity. In a variation, in which the individual could also be harmed, the authors additionally revealed that 27% are not only selfishly inclined but rather have spiteful preferences.

Assuming this 33/50/27 distribution and transferring the MSNE to n individuals, and assuming that players expect to play against the other two types equally

[7]Two vaccinations are required to achieve herd immunity; It is assumed that the altruist is only going to include the utility of the egoist in his or her utility maximization, and will not support the harmful behavior of the hooligan. There is no direct scientific evidence for this assumption, which is certainly open to discussion.

distributed, the vaccination rate is 89.02%. In a possible further step, altruistic priming could be used to increase either the number of altruists or the degree of altruism (analogous to Kanungo and Conger, 1993). For example, if the number of altruists increases by 5 pp, the vaccination rate increases by 0.51 pp (under the assumption that the players still assume the same distribution). At the same time, a to the other players visible increase in altruism to $\alpha = 3/5; \beta = 2/5$ would lead to a change in the vaccination rate of $+4.94$ pp.

Nevertheless, these extrapolations are subject to considerable uncertainty/errors and cannot be regarded as valid. In reality, of course, the player types are distributed much more diversely and it is also competed against the own player type. There is additionally the question of whether everyone is accurately aware of the intentions of the other players and how this information is subsequently processed (see subsection 2.3.2). Thus, for valid calculations it would be necessary to understand the game as a Bayesian game, whereby not all players have equal access to the information (see Gibbons, 1992), as well as to conduct a precise experimental determination of the utils/value assigned.

However, the considerations give a first insight into possible relationships, which can also be observed experimentally. Based on a conducted survey on hypothetical disease strains and different vaccines helpful for them, Hershey et al. (1994) measure the influence of altruism by varying the vaccination level and the emerging vaccination protection for the environment. In the general linear model (GLM) constructed by the authors, altruism has a significant effect ($p < .001$) on the decision to vaccinate. An increase of a point in the altruism scoring assigned by the authors would increase the inclination to vaccinate by 0.44 points on the measured nine point scale when altruism is promoted. If, instead, free-riding is promoted, the estimate of the effect increases even to 0.50 points, because, as shown in the previous game-theoretic explanations, this also increases the expected payoff of an altruist. Taking into account the effect of altruism, it is not surprising that the actual experimental findings indicate a deviation from the Nash equilibrium towards the utilitarian equilibrium (Chapman et al., 2012; Shim et al., 2012; Böhm et al., 2016). For instance, in a constructed vaccination game setting in which individual rewards exist, Chapman et al. (2012) show that fewer of the young than the old get vaccinated (equivalent to the Nash equilibrium and the theoretical elaborations by Wein (2021)). As the authors switch to a payoff conditional on the group success, the mean percentage of younger people vaccinated increases ($\beta = 0.14; p < .001$), resulting in a decrease in the mean percentage of participants infected ($\beta = -0.14; p = .001$). On the basis of an analysis of variance, the authors determine the motivation to protect others, hence indirect altruism, as the decisive mediator of this observed effect.

Since group and social identities in particular can affect altruism (Yamagishi and Mifune, 2008; Monroe, 1994; Margolis, 1984), but also themselves can have an influence on the vaccination decision in the form of e.g. bandwagoning ($p < .001$; Hershey et al., 1994), the social influence requires further determination.

2.3.1.2 Social Influence: Social Identity, Bandwagoning and Imitation

Individuals behave more positively towards members of their group than towards non-members. This relationship has not only been experimentally tested numerous times (Brewer and Kramer, 1986; Kramer and Goldman, 1995; De Cremer and Van Vugt, 1999; Simpson, 2006), it is also originally derived from the social identity theory (Tajfel and Turner, 1986; Abrams and Hogg, 1988).

Yet, this relationship also implies the inverse relationship that group orientation consequently influences the individual's behavior obliquely. It can be assumed that an individual experiences a higher utility if it acts aligned with the group orientation for the benefit of the group. In terms of the individual vaccination decision, this suggests that a pro-vaccination group orientation could have a positive effect on the vaccination decision, and, thus, the overall vaccination level.

Xia and Liu (2013) integrate this social influence into a game-theoretic analysis, equivalent to Bauch and Earn (2004). In a voluntary vaccination program, the authors assume a cost-minimizing individual anchored in a social network (see figure C.2, appendix). Depending on the strength and structure of social interactions as well as the interaction relationship/closeness and the number of possible influences, the steady state, which can be assumed to be equivalent to the Nash equilibrium, changes. Xia and Liu (2013) thereby introduce the conformity rate $\mathcal{P}$, "which is the probability that an individual finally convert to the formalized social opinion, or otherwise follows his/her cost-minimized choice" (p. 3). Including the SIR model, and, thus, a reproduction rate $\mathcal{R}_0$ and herd immunity V^{HI} equivalent to equation 2.18/2.20, results in

$$\sigma_i = \begin{cases} \tilde{\sigma}_i & \text{with probability} \quad \mathcal{P} \\ \hat{\sigma}_i & \text{with probability} \quad 1-\mathcal{P} \end{cases}, \tag{2.29}$$

whereas σ_i denotes the individual's decision to vaccinate. In this case, $\tilde{\sigma}_i$ represents a behavior according to the social network, while $\hat{\sigma}_i$ represents a behavior according to the cost minimization (equivalent to section 2.2). Thereby, the particular case $\mathcal{P} = 1$ implies the individual is a complete "social follower", while $\mathcal{P} = 0$ indicates a complete individual cost minimization.

However, Xia and Liu (2013) not only provide the game-theoretic framework, but additionally simulate the possible vaccination behavior within a high school using this framework. In a scenario based on the 2009 H1N1 influenza epidemic, the authors illustrate that, equivalent to Bauch and Earn (2004), the relative risk is a relevant influencing factor, but similarly, the conformity rate $\mathcal{P}$ is also a critical factor, leading to a significantly higher vaccination rate. In this calculation, they assume $\mathcal{R}_0 = 1.6$, a recovery rate of 0.312 and a network at the high school with close proximity interactions (less than 3m distance). This network has $N = 788$ nodes, an average node degree of 35 (the number of connected neighbors) and an average edge weight (which can be understood as social closeness) of 115 units. Using a Monte Carlo simulation, the authors run a series of simulations using different baseline willingness to vaccinate (see figure C.3, appendix). These simulations show that initial vaccination willingness is one of the significant factors determining how high the overall vaccination coverage will be. Indirectly via the conformity rate, a high initial willingness to vaccinate has a positive effect on the overall vaccination level, allowing negative effects arising from the cost ratio to be partially offset. In the hypothetical epidemic scenario, the authors show that with $\mathcal{R}_0 = 1.6$, a low but positive risk ratio ($0 < r \leq 0.8$), and a moderate conformity rate ($0.0 < \mathcal{P} \leq 0.6$) - i.e., a scenario that would require government intervention according to Bauch and Earn (2004) - a complete eradication of the disease appears possible, if the initial willingness to vaccinate is sufficiently high. At the same time, Xia and Liu (2013) show that with low initial willingness to vaccinate and/or an increasing cost ratio, especially in combination with a high conformity rate, an inverse effect occurs, indicating a lower vaccination rate than anticipated by standard theory.

The calculation of the two authors is based on the social identity theory (SIT), whereby other possible explanations for the positive effect of social influence appear. In this SIT, the type and closeness of social contact with other in-group members influences the social identity and, thus, the actual social influence (Xia and Liu, 2013). This social identity as such can be defined as "a self-definition in terms of social category membership" (Turner, 1999, p. 10) as well as "the individual's knowledge that he [or she] belongs to certain social groups together with some emotional and value significance to him [or her] of the group membership" (Tajfel, 1972, p. 292). Thus, in their individual utility maximization calculus, individuals facing the vaccination decision derive utility from a behavior aligned with the group behavior. The extent of this gain in utility is determined by an individually varying factor, like the conformity factor $\mathcal{P}$ introduced before. This group-induced social influence is also apparent when the groups are arbitrarily assigned (Tajfel et al., 1971). Social identity can consequently be understood as social comparison, in its meaning of Festinger (1954). Individuals derive utility from a positive comparison with the in-group as well as by a distinction from other existing out-groups. If this increase in utility by social comparison is sufficiently large, an accompanying high conformity factor $\mathcal{P}$ is to be expected, which implies that the substantive argumentation is subsidiary to the social distinction. In reality, this phenomenon occurs, for example, in the case of vaccine hesitancy by parent communities (Attwell and Smith, 2017; Attwell et al., 2018) or the compliance of the mask mandate, depending on the affiliation to Democratic or Republican parties in the US (Gelfand et al., 2022).

In addition to the SIT, further motivations for an (in-)group-oriented behavior can be identified and verified. For instance, bandwagoning can similarly be shown to have a significant effect ($p < .001$) on the vaccination decision (Hershey et al., 1994). Bandwagoning can be understood as simply jumping on the bandwagon of (non-)vaccination depending on the behavior of the social environment, no matter of the benefits and costs incurred. This behavior can either be a form of cost-avoidance strategy, avoiding the costs of information acquisition, processing, and subsequent deliberation, or it can arise out of a social learning process whereby individuals realize that it is smarter to rely on their social environment when making decisions (Bauch and Bhattacharyya, 2012).

Another avoidance strategy that has been experimentally shown to have an effect on the vaccination decision is the imitation/mimicking from behavior observed in the social network (e.g., Bauch, 2005; Fu et al., 2011). In the (industrial) economic context, imitation is, equally to the previous bandwagoning definition, considered as a social learning process, usually in repeated games, of the behavior performed by players who have a particular high payoff (Vega-Redondo, 1997; Schlag, 1998; Selten and Ostman, 2001). Thereby, the proportional imitation rule always presupposes a rational consideration of utility as well as a imitation solely of the behavior of exceptionally successful players (Schlag, 1998, 1999). Yet, especially in the psychological context, imitation is understood as social conformity and behavior induced by social pressure (Hodges, 2014; Lyons et al., 2007; Schein, 1954). In particular, the experiments of Asch (1948, 1951, 1956) show that imitation induced by social conformity/pressure, even when it is against personal belief, can be observed in a large proportion of individuals. For instance, 1/3 of the participants agreed with absolutely wrong answers only because the social surroundings agreed with them (Asch, 1956). Economically speaking, this implies that non-compliance with the social norm translates into a direct disutility for individuals. The avoidance of this direct disutility, especially since it is temporally directly apparent to the individuals (see impact of inter-temporal choice theory, Loewenstein and Thaler, 1989), is one underlying motivation of imitative behavior. Beyond that, however, subconscious imitation is also identifiable as "motivation" (Lyons et al., 2007). In this context, this is again to be understood as a decision cost avoidance process and as a possible adaptation in the sense of Selten (1998). While in the previous delimitations of imitation the imitated person is not assigned any value, this changes in the definition of the so-called faithful imitations (Hodges, 2014; Over and Carpenter, 2012; Nielsen and Blank, 2011). Faithful imitation implies in this regard the selection of the imitated person is not arbitrary and there is an existing relationship to this person. What exact relationship leads to this selection of an imitative object, is, nonetheless, debatable. Regardless of whether economic/monetary factors (see Schein, 1954; Schlag, 1998) or social factors, such as in-group membership, status or trust (see Over and Carpenter, 2012; Nielsen and Blank, 2011), lead to this choice, it can be assumed, economically speaking, that the track-record or social affiliation of the other person implies a higher expected utility than an uninfluenced individual decision. Consequently, social identity and social norms have an essential influence on the assessment of expected utility and, thus, the vaccination behavior.

2.3.2 Cognition

Cognition in the sense of Selten (1998) is defined as the reasoning processes happening in the human mind. These reasoning processes do not necessarily have to take place consciously and should be understood as the assessment of a specific situation, which, depending on the underlying motivation, can lead to a concrete outcome. Examples of these reasoning processes include assessing risks, perceiving losses, and evaluating the impact of one's own behavior.

2.3.2.1 Prospect Theory: Loss Aversion and Risk Perception

Prospect Theory allows to explain a number of phenomena seeming irrational according to traditional choice theory. Accordingly, both the *reference point* and *the distinction between gains and losses* affect the reasoning of individuals. This, in contrast to standard theory, different reasoning might additionally significantly influence the vaccination decision.

The Prospect Theory itself originates from Kahneman and Tversky (1979), but was elaborated in more detail in further subsequent works (see Tversky and Kahneman, 1991, 1992; Wakker and Tversky, 1993). Central in the initial design is the fact that, contrary to initial expectations, individuals reject a 50/50 lottery (Kahneman et al., 1982). According to the theory, this aversion increases with higher stakes. The authors explain this phenomenon with the different valuation of profits and losses, with losses being more prominent in the individual's weighting. This reasoning process implies a function based on a reference point

$$\pi(p) \cdot v(x) + \pi(q) \cdot v(y), \tag{2.30}$$

whereas v is the assigned value and π is the assigned decision weight of all different outcomes. This value is according to Kahneman and Tversky (1979) concave for gains and convex for losses, whereby concavity implicates aversion to risks and convexity aversion to losses. In the realm of losses this value function is, according to the theory, steeper than in the realm of gains. Concurrently, Tversky and Kahneman (1991, 1992) recognize that high probabilities tend to be under-weighted and small probabilities over-weighted. To allow for different weightings of gains and losses, Tversky and Kahneman (1992) introduce the Cumulative Prospect Theory:

$$V(f) = V(f^+) + V(f^-) \tag{2.31}$$

The prospects for gains and losses are

$$V^+ = \sum_{i=0...n} \pi_i^+(p) \cdot v(x_i) \quad \text{with the decision weight} \quad \pi_n^+ = w^+(p_n) \tag{2.32}$$

as well as

$$V^- = \sum_{i=-m...0} \pi_i^-(p) \cdot v(x_i) \quad \text{with the decision weight} \quad \pi_n^- = w^-(p_{-m}). \tag{2.33}$$

Tversky and Kahneman (1992) further propose a concrete form for the value and decision weights, which are respectively:

$$w^+(p) = \frac{p^\gamma}{[p^\gamma + (1-p)^\gamma]^\gamma} \quad \& \quad w^-(p) = \frac{p^\delta}{[p^\delta + (1-p)^\delta]^\delta} \tag{2.34}$$

Since γ and δ are commonly assumed to be 0.61 and 0.69, respectively, this reflects the differences in losses and gains and different perceptions of risk (Tversky and Kahneman, 1992).

Thus, when applied to the vaccination decision, (1) loss aversion, (2) reference points, and (3) altered risk perceptions can similarly be assumed to have an influence.

(1) Aversion to losses may influence individual utility maximization calculus and, hence, the overall vaccination rate. Thus, equivalent to the Prospect Theory, it can be assumed that utility losses and costs are taken into account to a greater extent. This applies to both the evaluation of payoffs in the game-theoretic assessment and the initial utility assessments, as these can be understood as expected utilities. Due to the changed valuation of the payoffs, it can be assumed that the "threat" $\{\overline{V}, \overline{V}\}$ becomes more important. From a game-theoretic perspective, this results in a higher incentive to use the strategy V. Since it can be assumed that other players do not anticipate the loss aversion, this leads to a higher vaccination rate than expected. In addition, this increases the likelihood of a tacit collusion, if the vaccination game is considered a repeated game. This would similarly have a positive effect on the vaccination rate. How strong and in which direction the effect of loss aversion is in the individual utility evaluation depends essentially on the reference point set.

(2) Reference points are thereby deciding on what is considered loss and gain in the vaccination decision in the first instance. Depending on whether vaccination or non-vaccination is seen as the status quo, the other, i.e. U_i^V or $U_i^{\overline{V}}$, is being subjected to utility evaluation. Thus, the loss of freedom due to possible restrictions and the potential adverse health effects of an infection can be perceived as losses of non-vaccination if vaccination is the status quo, and, consequently, the reference point. However, the reverse scenario whereby non-vaccination is seen as a reference point can also occur, resulting in an "overestimation" of the adverse effects of vaccination. This can lead to a scenario in which, according to standard theory, $U_i^V = U_i^{\overline{V}}$ applies, but depending on the reference point $U_i^V > U_i^{\overline{V}}$ and, hence, $V \succ \overline{V}$ or $U_i^V < U_i^{\overline{V}}$ and, hence, $V \prec \overline{V}$ holds. It can therefore be assumed that a small group of individuals will decide for or against vaccination, depending on their set reference point. Depending on the framing and other external influences, this effect may cause standard theory to under- or overestimate vaccination rates. This so-called status quo bias, i.e. that people rarely deviate from previous behavior because of the reference point set (Tsutsui et al., 2010), has also been verified in actual vaccination behavior. Specifically, for influenza vaccination behavior, past vaccination behavior has been one of the strongest predictors of future vaccination behavior (Sendi et al., 2004; Nichol and Hauge, 1997).[8] At the same time, this change in perception, in contrast to standard theory, leads to an additional underestimation of high probabilities. Moreover, in contrast to the standard theory, this altered risk perception also leads to an underestimation of high probabilities.

(3) Altered perceptions of risks result in an overestimation of the commonly small risk of adverse effects caused by vaccination. As the risk ratio/relative risk r is the essential factor for determining the general vaccination level in the game-theoretic calculations (see e.g. Bauch and Earn, 2004; Xia and Liu, 2013), it can be assumed that an overestimation of the risks from vaccination r_V leads to a decrease in the vaccination level. With a higher r_V the relative risk r also increases, thereby causing the vaccination probability P^* and, thus, the expected vaccination level to decrease in an endemic state (see equation 2.24). Since not only r_V is being overestimated, but also the risk of infection r_I is being underestimated, this negative effect and, hence, the deviation from the standard theory is further enhanced.

2.3.2.2 Heuristics and Cognitive Biases: The Omission Bias and more

In addition to the already addressed status quo bias, there are other heuristics and biases that can influence individuals' reasoning. These are briefly presented below:

[8] Nonethelesss, it is reasonable to assume that only part of the variation is due to status quo bias, and the remaining part is due to other predeterminants of the vaccination decision, which remain constant over time.

The Omission Bias implicates that many people tend to prioritize potentially harmful omissions over less harmful action (Asch et al., 1994). Economically speaking, this indicates that $V \prec \overline{V}$ can be valid, even if $U_i^V > U_i^{\overline{V}}$ holds, because $\overline{V}$ is considered an omission behavior. Thus, it can be assumed that omission affects the individuals' utility ratio such that $U_i^V < U_i^{\overline{V}}$ holds. This bias can be observed in the individuals' vaccination behavior equivalent to the theoretically presented way (see Asch et al., 1994; Spranca et al., 1991; Ritov and Baron, 1990). More specifically, Asch et al. (1994) indicate that parents who exhibit vaccination hesitancy are significantly more likely to be subject to the omission bias ($p = .004$).

The Optimism Bias implicates the "tendency to be more optimistic about a particular health risk, believing it is greater for other people than for themselves" (Dubov and Phung, 2015, p. 2533). This, again, implies an underestimation of r_I and, hence, a lower probability P^* of vaccination than anticipated. However, it remains questionable to what extent this has a similar effect on the vaccination risk r_V.

The Ambiguity Aversion implicates the tendency to favor known risks/events over unknown risks/events (Fox and Tversky, 1995). Whilst the risk of infection of a new disease is researched with top priority and a great amount of transparency, a lot of in-transparency exists about possible (long-term) adverse effects caused by a vaccination.[9] Thus, a tendency to expose oneself to the "known" risk of infection exists - with the effect on the utility calculus as presented for the omission bias. In particular, a qualitative study works out that among Australian parents both vaccinators and non-vaccinators show a lean towards certain risks (Bond and Nolan, 2011). However, the authors also point out that these two groups differ: Vaccinators see the uncertainty in diseases unknown to them, while non-vaccinators describe diseases including their course/treatment as certain and see uncertainty in the vaccine.

The Availability Heuristic implicates the tendency "to make judgments of likelihood or frequency based on ease of recall rather than on actual probabilities" (Blumenthal-Barby and Krieger, 2015, p. 539). This heuristic, originally based on Kahneman et al. (1982), can also be applied to the individual vaccination decision. If, for example, a vaccine scare has only recently been present to an individual, this heuristic will lead to an overestimation of the probability of adverse effects r_V. This, again, implies a lower probability P^* of vaccination than anticipated (see further remarks on vaccine scares by Bauch and Earn, 2004).

The Confirmation Bias implicates the tendency to seek or interpret evidence in ways that are partial to existing beliefs (Nickerson, 1998). This bias is also evident in experiments in which information about a vaccine are presented to individuals and its evaluation is analyzed (e.g. Meppelink et al., 2019; Attwell et al., 2018).

[9] Uncertainty about long-term consequences of infection is often neglected - see "Mental Accounting" (Thaler, 1985) and "Anchoring Effect" (Tversky and Kahneman, 1974).

2.3.3 Adaptation

Adaptation in the sense of Selten (1998) is defined as "kind of learning behaviour [sic] [...] without any powers of reasoning" (p. 414). Thus, it can be considered as any behavior that is not (even indirectly) based on economic incentives, but is characterized by randomness or by routines. Examples arising from the vaccination decision are random decisions for or against vaccination (as indicated by cognitive hierarchy theory, Stahl and Wilson, 1995; Camerer et al., 2004), unconscious imitation (Lyons et al., 2007), or the influence of nudges (summarized in Reñosa et al., 2021). Nonetheless, since both psychologists and economists assume reasoning in almost every observable behavior, this decision process is still very underrepresented in research and can be understood as an error term, i.e., a deviation between expected and actually observed behavior.

2.4 Interim Conclusion

Individual utility as well as the game-theoretic analysis without the inclusion of behavioral economics indicate that, as expected, herd immunity cannot be achieved without government intervention. The primary factor influencing vaccination rates is the relative risk r. For each positive relative risk, there is an equilibrium lying below the threshold for a complete eradication of the disease. Furthermore, as the relative risk increases, the vaccination rate will decrease.

Inclusion of behavioral economic aspects expands the model such that other factors besides the risk ratio influence the decision to vaccinate. These factors increase the variance in expected vaccination rates, allowing for vaccination rates above the required threshold. In contrast, these factors can also cause vaccination rates to be below the expected level and, therefore, inevitably below the required threshold.

However, the inclusion of the behavioral economic factors further increases uncertainty - especially with respect to possible government intervention. First, the behavioral and psychological factors are difficult to quantify. In particular, because of many overlaps between the concepts, it cannot be ruled out that some of the variation found in individual studies is attributable to other factors. Furthermore, it cannot be excluded that possible interaction effects strengthen/weaken these effects. Second, the exact effect directions are not precisely determinable. These effect directions depend on the concrete initial situation and possible further influences. There may be situations in which more altruism has the game-theoretic consequence of lowering vaccination rates. Concurrently, uncertainties and incomplete information can lead to a decrease in the level of altruism and spitefulness (Ely and Yilankaya, 2001; Possajennikov, 2000)), which changes the vaccination rate as well. The question remains how these factors identified influence possible government interventions.

3 Government Intervention

Equivalent to the distinction between hard and soft law on an intergovernmental level (see Scott and Trubek, 2002), the behavioral economic factors identified allow a distinction to be made between hard and soft government intervention possibilities. Hard government intervention is understood as a legally binding intervention. In contrast, a non-legally binding intervention is a soft type of government intervention. In the following, the two types of intervention are exemplified with respect to the Covid pandemic and the debate about mandatory vaccination versus a vaccination lottery.

3.1 Hard Government Intervention: Mandatory Vaccination

The hard, legally binding government intervention is aimed at correcting the undersupply of the public good through a mandatory provision of it. In the case of the Covid pandemic, this means that the state legally requires citizens to be vaccinated so that a critical threshold is reached and Covid is completely eradicated.

Nonetheless, the "hardness" of the intervention by the government can be adjusted. The government not only has the means to influence the utility maximization calculations of individuals through other legally binding interventions not directly obliging them to vaccinate. Moreover, in the case of mandatory vaccination, it is possible to vary the legal consequences and, hence, the severity of the intervention. Interventions such as partial lockdowns, mandatory testing, or other restrictions imposed on the unvaccinated increase the costs of non-vaccination and/or the utility of vaccination (see individual utility assement; equation 2.1). This may to some extent internalize the positive externalities and have a corrective effect (as shown in figure 2.1). A mandatory vaccination may also indirectly influence individual choices, but it does not necessarily do so. The individual is again faced with weighing the utility of two scenarios: vaccination and no punishment or non-vaccination and punishment. Depending on the amount of the fine and its compliancy, the degree of intervention can be adjusted. A purely monetary fine, as discussed in Germany or partially implemented in Austria, would have the same effect according to standard economic theory as a monetary (lump-sum) transfer for vaccination. If this monetary fine has a fixed value, this leads to a regressive burden, which suggests that lower-income individuals are more likely to comply with the regulations.

To estimate compliance and, hence, the concrete impact, it is necessary to determine the attitudes regarding mandatory vaccination. Negative attitudes towards an intervention (initially indicated by α; equation 2.1) could lead to secondary adverse effects making the costs of enforcement comparatively high. Based on the SOEP CoV special survey, Graeber et al. (2021) extract exactly these attitudes in

Germany and identify four different groups of individuals in the first instance: 1. Anti-vaccination (do not get vaccinated voluntarily and oppose a policy of mandatory vaccination; share of total: 22%), 2. Anti-duty (voluntarily: yes; mandatory: no; share of total: 29%) 3. Passengers (voluntarily: no; mandatory: yes; share of total: 8%) & 4. Pro-vaccination (voluntarily: yes; mandatory: yes; share of total: 41%). Thus, a total of 30% are affected by a possible obligation to vaccinate, whereby 8% of them can be assumed to adjust their decision even at lower fines. Yet, with 29% of the individuals, the risk exists that although they would voluntarily get vaccinated, they might adjust their decision or not comply in case of mandatory vaccination. In addition, in a logit regression controlling for big five personality traits, health risks, and political preference, Graeber et al. (2021) show that gender ($\beta_{female} = -0.100; p = .004$) and age ($\beta = 0.004; p = .006$) influence voluntary vaccination and attitudes towards mandatory vaccination to the same amount. In contrast, the effects for tertiary education ($p = .001$) and income ($p = ns.$) differ between the probability of being vaccinated and being positive towards mandatory vaccination. An increase in net household income of EUR 1,000 increases the probability of vaccination by 2.5 log points ($p = .045$), but the probability of having a positive attitude towards compulsory vaccination by only 0.4 log points ($p = ns.$). Concurrently, tertiary education is associated with a 13.1 log point higher probability of being vaccinated ($p < .001$) and a 4.9 log point lower probability of being positive towards mandatory vaccination ($p = ns$). Considering, as presented by the authors, that vaccination probability is a major determinant of the attitude towards mandatory vaccination, it can be assumed that an insufficient compliance cannot be excluded given insufficient punishment.

3.2 Soft Government Intervention: Vaccination Lottery

The soft, non legally binding government intervention is also aimed at correcting the undersupply of the public good. In the case of Covid, this could be promoting altruism and social norms as vaccination protects the (immediate) environment (Abdallah and Lee, 2021), pinpointing losses to trigger loss aversion, or targeting the various heuristics and biases, such as declaring the non-vaccination an active action and the vaccination an omission to trigger the omission bias (as demonstrated by Tversky and Kahneman, 1985).

Another soft form of intervention discussed in the course of the Covid pandemic and actually implemented in the U.S. (Ohio) is the vaccination lottery. The intention is to make use of biased risk perceptions (as indicated in the Cumulative Prospect Theory; Tversky and Kahneman, 1992). Individuals, who tend to overestimate small probabilities, also overestimate the small probability of winning at the lottery, which is the lottery's leverage. These assumptions are accordingly confirmed in the qualitative part of the evaluation of the SOEP CoV by Graeber et al. (2021). 53.3% of the non-vaccinators stated as reasoning that the danger of the virus would be overestimated, implying the underestimation of large probabilities while overestimating small probabilities.

In a controlled experiment, Kim (2021) compares a lump-sump transfer with the vaccination lottery. As stated before, this lump-sump transfer can be seen as an inverse form of a purely monetary mandatory vaccination (without taking into account the effect of loss aversion). The experimental design provides for one control and three treatment groups. The treatment differentiates between a transfer in case of herd immunity, a lottery with distribution in case of herd immunity and an unconditional lottery, with all options having the same budget available for distribution. In this game, players contribute in four rounds, in which they decide on participation or non-participation (i.e., vaccination or non-vaccination) for the remainder of the game and receive a payoff in points. The results of Kim (2021) show that in the case of the lottery[10] a total of 74% participate, indicating a vaccination rate of 74%. This is 22 pp higher than the control group (p = .049) and 30 pp higher compared to the transfer group (p = .008). In addition, Kim (2021) shows descriptively, based on individuals' ex-ante determined probability estimation type, that 16 pp more individuals in the "small probability overweight" group responded to the lottery as an incentive.[11]

3.3 Discussion

When evaluating government intervention, a fundamental differentiation between primary and secondary effects has to be made. A primary effect in this context may be regarded as a direct, instantaneous effect. In the case of a lump-sum transfer or mandatory vaccination with monetary fines, the primary effect represents a change in the utility maximization calculus. A secondary effect represents a change in other parameters that can strengthen/weaken the primary effect subsequently. In this case, subsequently can imply both direct influence on the primary effect or long-term consequences. Related to the example, this could entail that the government's hard intervention triggers an encroachment on individual autonomy (see α; equation 2.1), a lowering of the willingness to be altruistic, a loss aversion, or other biases. Since mandatory vaccination with monetary fines triggers individuals' loss aversion, it appears that, while it does not differ from a lump-sump transfer in the primary effect, it differs significantly from it in the overall effect. A long-term secondary effect may, for example, be a resulting change in behavior for a re-occurring pandemic situation, resulting from the introduction of mandatory vaccination.

[10]Unconditional and conditional lotteries were pooled as no significant differences existed.

[11]No statements about significance given.

With regard to the exemplary debate about a mandatory vaccination versus a vaccination lottery, it can be concluded - in addition to the general fact that individual studies should not be overestimated - that studies such as the one by Kim (2021) give a first indication of possible primary effects, but do not (cannot) represent the overall effect. It can be assumed that, although the experiment identifies the primary effect of a lottery, secondary effects might mitigate the overall effect. Consequently, the effect is likely to be overestimated. Still, it can be deduced that the thesis of a vaccination lottery being a corrective governmental intervention according to the economic definition cannot be falsified. Nonetheless, uncertainty exists about the external validity. Currently, it can only be assumed that the behavior observed in the experiment can also be replicated in actual decisions regarding health protection. Although Ohio saw a 30% increase in vaccination rates as a result of the lottery (Kim, 2021), this cannot be considered a causal effect since only the rate within the state was examined. Instead, it is necessary to clarify on the basis of a counterfactual, such as an equivalent state that has not implemented this lottery, what proportion of the increase is actually due to the lottery.

Yet, the same uncertainty applies to mandatory vaccination. Neither is it certain what the concrete primary effect is, respectively which compliance rate is associated with which level of sanction, nor is its secondary effect determined. Nevertheless, there is no question that the state can enforce mandatory vaccination and adjust the sanctions to ensure that enough people get vaccinated (see China). Instead, the question is with which costs of monitoring and enforcement this can ultimately be achieved.

Concurrently, every non-totalitarian government has to consider fundamental rights, as the citizen's rights of defense against the government, as well as a test of proportionality for any governmental encroachment on them. This test of proportionality requires the absence of a milder form of intervention. Because the vaccination lottery has a behavioral economic rationale, cannot be falsified in experiments, and is subject to the same uncertainty regarding secondary effects as a mandatory vaccination, it should be prioritized as a softer intervention. The same applies to other, softer influencing factors that have been elaborated in this work.

Albeit these softer forms of intervention often come with less cost and, instead, imply targeted communication and framing, they require in-depth data and research. Only through reliable data material and in-depth research it can be clarified when an intervention possibility arises from the mentioned behavioral economic factors, in which cases adverse effects can occur and how large the multiplier of certain interventions is.

4 Conclusion

"Remember that all models are wrong; the practical question is how wrong do they have to be to not be useful." (Box and Draper, 1987, p. 424) - The example of the individual vaccination decision demonstrates how complex and difficult it is to model human behavior. Game-theoretic modeling of vaccination behavior indicates that the risk ratio (vaccination vs. disease) alone is crucial in determining the resulting vaccination level, which cannot, in any case, reach herd immunity. The modeling is based on a number of assumptions: unified preferences, complete information, rational information processing, and an epidemiological pandemic course according to the SIR Model.

Additional factors, which can influence a vaccination decision in both directions, emerge from behavioral economics research. Since these effects point in both directions, it can be assumed that a pandemic will, on average, follow the game-theoretic considerations according to standard theory. Thus, this type of modeling possesses usefulness for roughly estimating a pandemic course and a general justification for government intervention. With different vaccination rates occuring across states, the limitations of this model become apparent. As isolated individual cases must be considered to explain vaccination hesitancy and to differentiate between government interventions, this general model is not sufficient. Instead, it is necessary to extend the model by the behavioral economic factors. This literature-based reappraisal of determinants highlights that different preferences (such as altruism), social influence, loss aversion, misperceptions of risk, as well as other heuristics and biases, can, besides the risk ratio, positively and negatively influence individual vaccination decisions. Even if the exact effects cannot precisely be determined, the inclusion of these factors in the modelling possesses value, as it results in softer government intervention options.

This surface representation of the behavioral economic factors influencing the vaccination decision provides the basis for more in-depth research, which is essential to eliminate inefficiencies through soft interventions. Therefore, it is necessary to elaborate when which effect (direction and coefficient) can be anticipated and which secondary effects result from possible interventions. This requires both qualitative and quantitative research, as well as inter- and intra-disciplinary collaboration. In addition, other game-theoretic scenarios need to be added. Given the above, what results can be expected when adding other strategies such as contact avoidance? How do the results change when the government is seen as a player? How is the outcome in multi-round games - based on the assumption that pandemics will occur more often?

Appendix A List of Variables

All variables which are necessary to understand the corresponding remarks:

Symbol	Meaning
I	Infection Prevention // Infection
α	Individual Autonomy
f	Freedom
a	Personal Liberty
c	Costs
c_V	Costs of Vaccination
r_I	Morbidity Risk Infection
r_V	Morbidity Risk Vaccination
r	Risk Ratio (r_V/r_I)
$\pi_{V_{-i}}$	Risk of Infection
π_0	Risk of Infection without any Vaccination
π	Prospect Theory: Probability
V_{-i}	Vaccination Level of the Population
V	Vaccination - Prospect Theory: Value Function
$\overline{V}$	Non-Vaccination
HI	Herd Immunity
P	Probability to Vaccinate
P^*	Probability to Vaccinate in Equilibrium
Q	Probability to Vaccinate with Strategy Q
ε	Proportion of the Population - Prospect Theory: Weighting Gain
$\mathcal{R}_0$	Reproduction Rate
β	Mean Transmission Rate
μ	Mean Birth and Death Rate
γ	Mean Infectious Period
S	Susceptible
R	Recovered
$\mathcal{P}$	Conformity Rate
$\tilde{\sigma}_i$	Behavior according to Social Network
$\hat{\sigma}_i$	Behavior according to Cost Minimization
v	Prospect Theory: Value
δ	Prospect Theory: Weighting Loss

Appendix B Further (Mathematical) Specifications

Bauch and Earn, 2004

- This part is entirely based upon Bauch and Earn (2004) and only serves the purpose of providing understanding -

Equation 2.23 – Equation 2.24:

$$\pi_{V_{-i}} = \frac{\mathcal{R}_0(1+f)\hat{S}\hat{i}}{\mathcal{R}_0(1+f)\hat{S}\hat{i} + f\hat{S}} \tag{B.1}$$

equals the infection probability, as $\hat{S}$ and $\hat{i}$ are constant in an endemic state. This yields

$$\pi_{V_{-i}} = 1 - \frac{1}{\mathcal{R}_0(1 - V_{-i})}. \tag{B.2}$$

This can be substituted into the original equation for the MSCSNE

$$r < \pi_{V_{-i}}, \tag{B.3}$$

from which

$$\mathcal{R}_0(1 - r) > 1 \tag{B.4}$$

follows. Thus, from

$$\pi_{V_{P*}} = r \tag{B.5}$$

Equation 2.24,

$$P^* = 1 - \frac{1}{\mathcal{R}_0(1 - r)}, \tag{B.6}$$

can be concluded in case of the MSCSNE.

Baseline Utility

Baseline utils assumed in the game-theoretical considerations in case of a normal player type:

1) Two Player Game:

Szenario	Payoff for i
$U_i = V; U_j = V$	8
$U_i = V; U_j = \overline{V}$	5
$U_i = \overline{V}; U_j = V$	10
$U_i = \overline{V}; U_j = \overline{V}$	-1

2) Three Player Game:

Szenario	Payoff for i
$U_i = V; U_j = V; U_k = V$	8
$U_i = V; U_j = \overline{V}; U_k = V$	8
$U_i = V; U_j = V; U_k = \overline{V}$	8
$U_i = V; U_j = \overline{V}; U_k = \overline{V}$	6
$U_i = \overline{V}; U_j = V; U_k = V$	10
$U_i = \overline{V}; U_j = \overline{V}; U_k = V$	5
$U_i = \overline{V}; U_j = V; U_k = \overline{V}$	5
$U_i = \overline{V}; U_j = \overline{V}; U_k = \overline{V}$	-1

For other preference types, the utils are scaled in accordance with α and β.

Appendix C Further Figures

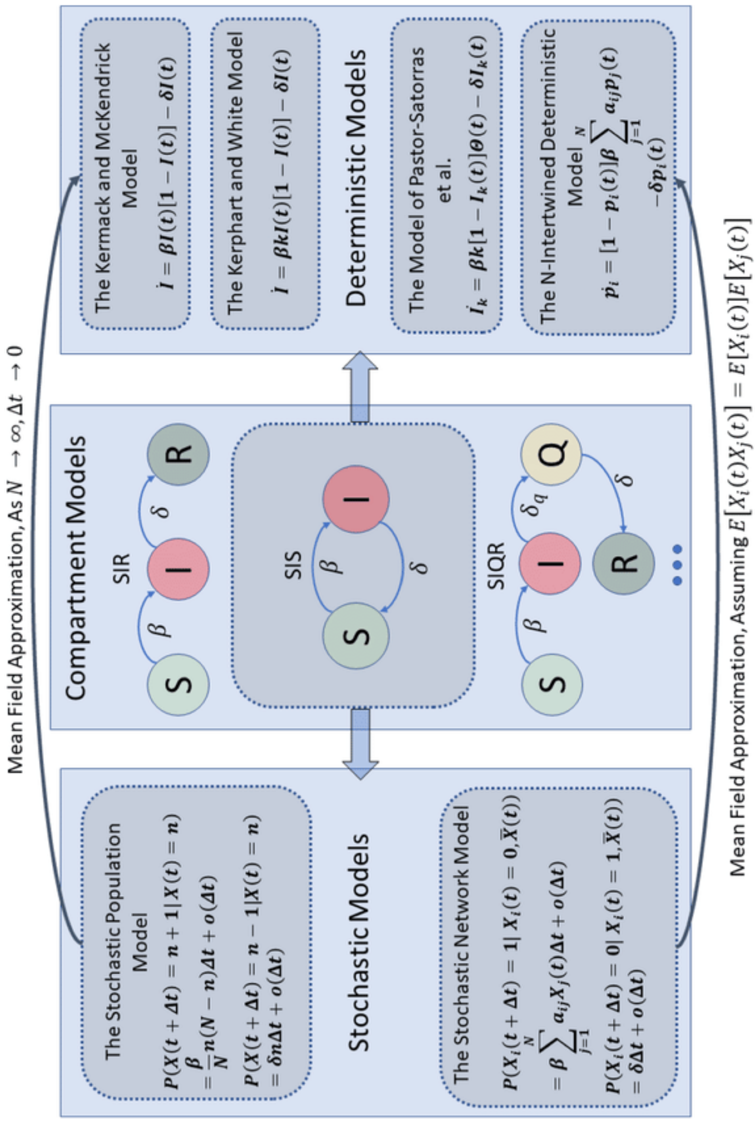

Figure C.1: A taxonomic summary of well-kown epidemic models and their connection

A detailed breakdown of the models used for epidemiological modeling of pandemics. The game theory analyses used and most economic papers use only the simplifying SIR model.

(Source: Huang and Zhu (2022))

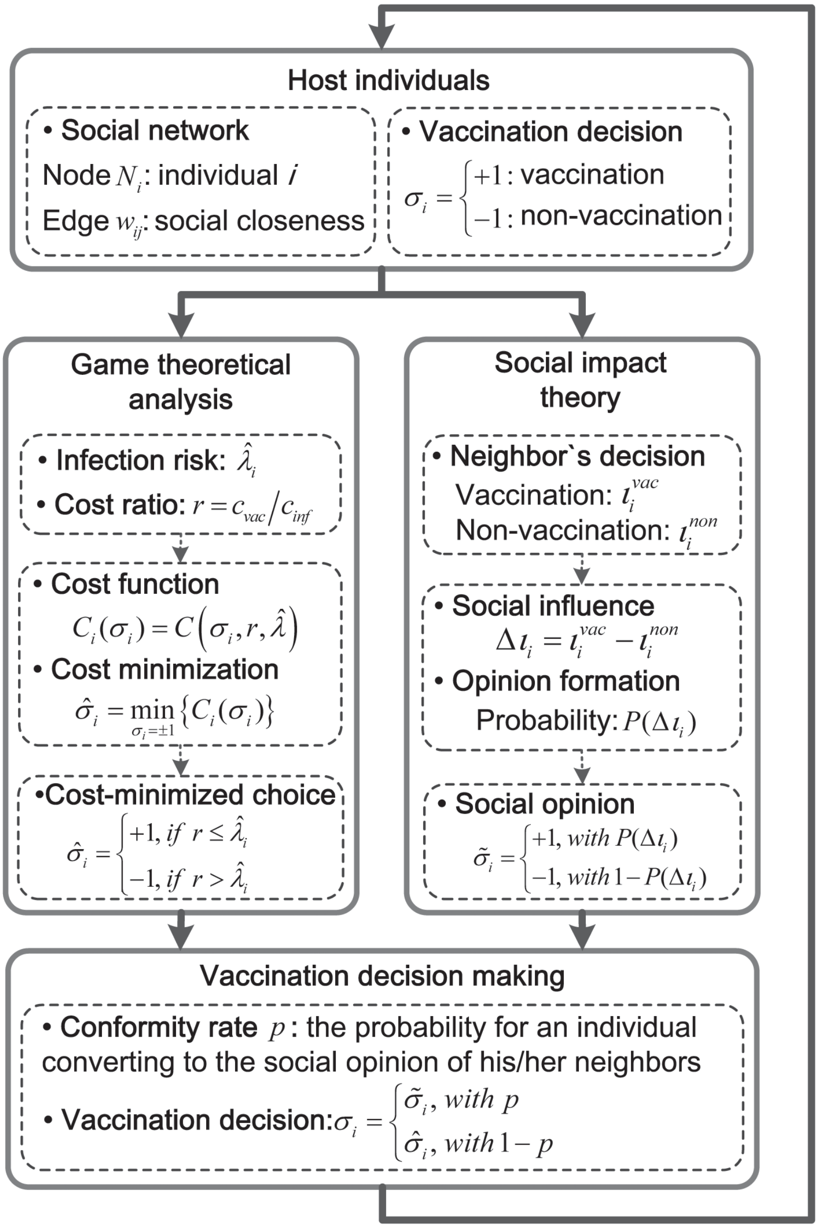

Figure C.2: The proposed model of individuals vaccination decision making (incorporating social influence)

(Source: Xia and Liu (2013))

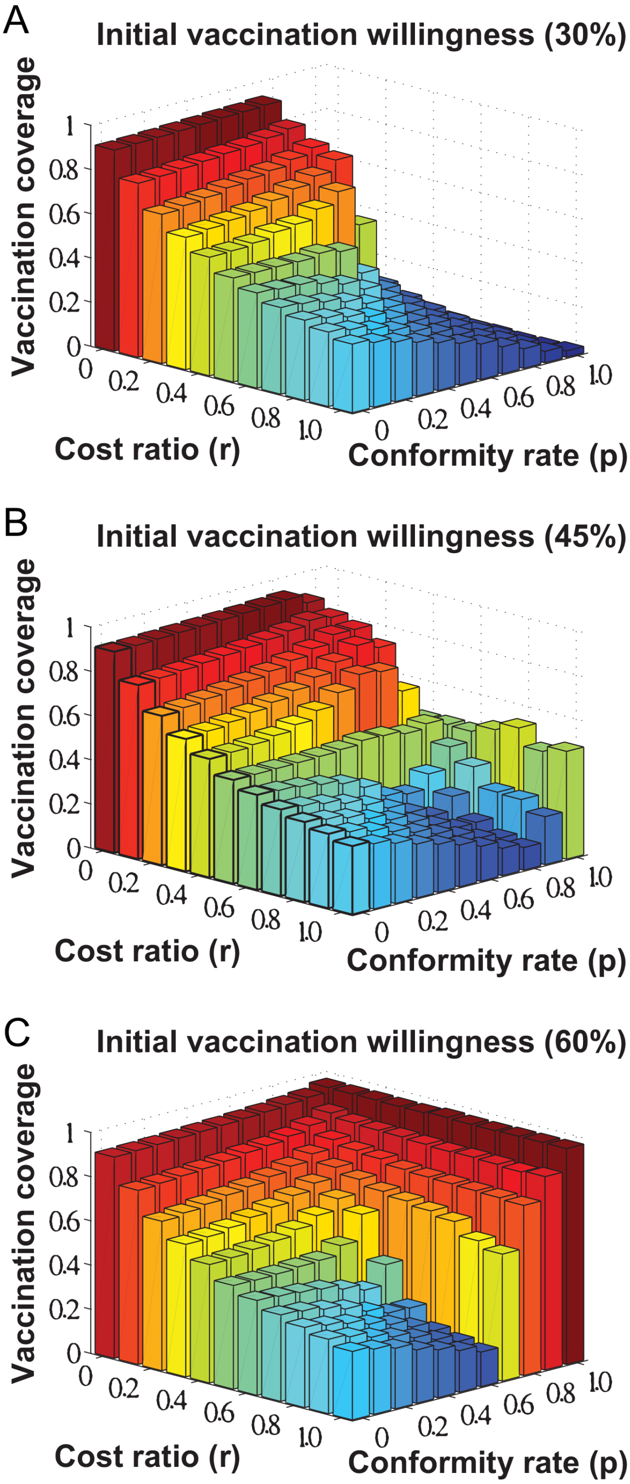

Figure C.3: Vaccine coverage at the steady state of individuals decision making (incorporating social influence)

Given an initial willingness to vaccinate, the vaccination level is simulated for different configurations of cost ratio and compliance rate. Parameters of the Monte Carlo simulation: $\mathcal{R}_0 = 1.6$, recovery rate= 0.312, social network with $N = 788$ nodes, average node degree of 35 units & average edge weight 115 units.

(Source: Xia and Liu (2013))

Bibliography

Abdallah, D. A. and Lee, C. M. (2021). Social norms and vaccine uptake: College students' covid vaccination intentions, attitudes, and estimated peer norms and comparisons with influenza vaccine. *Vaccine*, 39(15):2060–2067.

Abrams, D. and Hogg, M. A. (1988). Comments on the motivational status of self-esteem in social identity and intergroup discrimination. *European journal of social psychology*, 18(4):317–334.

Acemoglu, D., Chernozhukov, V., Werning, I., and Whinston, M. D. (2021). Optimal targeted lockdowns in a multigroup SIR model. *American Economic Review: Insights*, 3(4):487–502.

Alam, M., Kuga, K., and Tanimoto, J. (2019). Three-strategy and four-strategy model of vaccination game introducing an intermediate protecting measure. *Applied Mathematics and Computation*, 346:408–422.

Alvarez, F., Lippi, F., and Argente, D. (2020). Simple planning problem for covid-19 lockdown. *Working Paper Series National Bureau of Economic Research*.

Anderson, R. M. and May, R. M. (1992). *Infectious diseases of humans: dynamics and control*. Oxford university press.

Andreoni, J. (1989). Giving with impure altruism: Applications to charity and ricardian equivalence. *Journal of political Economy*, 97(6):1447–1458.

Andreoni, J. and Miller, J. (2002). Giving according to garp: An experimental test of the consistency of preferences for altruism. *Econometrica*, 70(2):737–753.

Asch, D. A., Baron, J., Hershey, J. C., Kunreuther, H., Meszaros, J., Ritov, I., and Spranca, M. (1994). Omission bias and pertussis vaccination. *Medical decision making*, 14(2):118–123.

Asch, S. E. (1948). The doctrine of suggestion, prestige and imitation in social psychology. *Psychological review*, 55(5):250–276.

Asch, S. E. (1951). Effects of group pressure upon the modification and distortion of judgments. *Organizational influence processes*, 58:295–303.

Asch, S. E. (1956). Studies of independence and conformity: I. a minority of one against a unanimous majority. *Psychological monographs: General and applied*, 70(9):1–70.

Attwell, K. and Smith, D. T. (2017). Parenting as politics: social identity theory and vaccine hesitant communities. *International Journal of Health Governance*, 22(4):182–198.

Attwell, K., Smith, D. T., and Ward, P. R. (2018). 'the unhealthy other': how vaccine rejecting parents construct the vaccinating mainstream. *Vaccine*, 36(12):1621–1626.

Balafoutas, L., Kerschbamer, R., and Sutter, M. (2012). Distributional preferences and competitive behavior. *Journal of Economic Behavior & Organization*, 83(1):125–135.

Barrett, S. (2003). Global disease eradication. *Journal of the European Economic Association*, 1(2-3):591–600.

Bauch, C. T. (2005). Imitation dynamics predict vaccinating behaviour. *Proceedings of the Royal Society B: Biological Sciences*, 272(1573):1669–1675.

Bauch, C. T. and Bhattacharyya, S. (2012). Evolutionary game theory and social learning can determine how vaccine scares unfold. *PLoS computational biology*, 8(4):e1002452.

Bauch, C. T. and Earn, D. J. (2004). Vaccination and the theory of games. *Proceedings of the National Academy of Sciences*, 101(36):13391–13394.

Bjørnstad, O. N., Finkenstädt, B. F., and Grenfell, B. T. (2002). Dynamics of measles epidemics: estimating scaling of transmission rates using a time series SIR model. *Ecological monographs*, 72(2):169–184.

Blumenthal-Barby, J. S. and Krieger, H. (2015). Cognitive biases and heuristics in medical decision making: a critical review using a systematic search strategy. *Medical Decision Making*, 35(4):539–557.

Böhm, R., Betsch, C., and Korn, L. (2016). Selfish-rational non-vaccination: Experimental evidence from an interactive vaccination game. *Journal of Economic Behavior & Organization*, 131:183–195.

Bolton, G. E. and Ockenfels, A. (2000). ERC: A theory of equity, reciprocity, and competition. *American economic review*, 90(1):166–193.

Bond, L. and Nolan, T. (2011). Making sense of perceptions of risk of diseases and vaccinations: a qualitative study combining models of health beliefs, decision-making and risk perception. *BMC public health*, 11(1):1–14.

Box, G. E. and Draper, N. R. (1987). *Empirical model-building and response surfaces*. John Wiley & Sons.

Brewer, M. B. and Kramer, R. M. (1986). Choice behavior in social dilemmas: Effects of social identity, group size, and decision framing. *Journal of personality and social psychology*, 50(3):543–549.

Buchanan, J. M. (1968). *Demand and supply of public goods*. Rand McNally & Company.

Camerer, C. F., Ho, T.-H., and Chong, J.-K. (2004). A cognitive hierarchy model of games. *The Quarterly Journal of Economics*, 119(3):861–898.

Chapman, G. B., Li, M., Vietri, J., Ibuka, Y., Thomas, D., Yoon, H., and Galvani, A. P. (2012). Using game theory to examine incentives in influenza vaccination behavior. *Psychological science*, 23(9):1008–1015.

De Cremer, D. and Van Vugt, M. (1999). Social identification effects in social dilemmas: A transformation of motives. *European Journal of Social Psychology*, 29(7):871–893.

Dubov, A. and Phung, C. (2015). Nudges or mandates? the ethics of mandatory flu vaccination. *Vaccine*, 33(22):2530–2535.

Dybvig, P. H. and Spatt, C. S. (1983). Adoption externalities as public goods. *Journal of Public Economics*, 20(2):231–247.

Eichenbaum, M. S., Rebelo, S., and Trabandt, M. (2021). The macroeconomics of epidemics. *The Review of Financial Studies*, 34(11):5149–5187.

Ely, J. C. and Yilankaya, O. (2001). Nash equilibrium and the evolution of preferences. *journal of Economic Theory*, 97(2):255–272.

Eshel, I. (1996). On the changing concept of evolutionary population stability as a reflection of a changing point of view in the quantitative theory of evolution. *Journal of mathematical biology*, 34(5):485–510.

Eshel, I., Samuelson, L., and Shaked, A. (1998). Altruists, egoists, and hooligans in a local interaction model. *American Economic Review*, pages 157–179.

Falk, A. and Fischbacher, U. (2006). A theory of reciprocity. *Games and economic behavior*, 54(2):293–315.

Farboodi, M., Jarosch, G., and Shimer, R. (2020). Internal and external effects of social distancing in a pandemic. *Covid Economics*, 9:22–58.

Fehr, E. and Schmidt, K. M. (1999). A theory of fairness, competition, and cooperation. *The quarterly journal of economics*, 114(3):817–868.

Fehr, E. and Schmidt, K. M. (2006). The economics of fairness, reciprocity and altruism – experimental evidence and new theories. In Kolm, S.-C. and Ythier, J. M., editors, *Foundations*, volume 1 of *Handbook of the Economics of Giving, Altruism and Reciprocity*, chapter 8, pages 615–691.

Festinger, L. (1954). A theory of social comparison processes. *Human Relations*, 7:117–140.

Fisher, I. (1892). Mathematical investigations in the theory of value and price. *Transactions of Connecticut Academy of Arts and Sciences*, 9. (Augustus M. Kelley, New York, 1965).

Fox, C. R. and Tversky, A. (1995). Ambiguity aversion and comparative ignorance. *The quarterly journal of economics*, 110(3):585–603.

Francis, P. J. (1997). Dynamic epidemiology and the market for vaccinations. *Journal of Public Economics*, 63(3):383–406.

Fu, F., Rosenbloom, D. I., Wang, L., and Nowak, M. A. (2011). Imitation dynamics of vaccination behaviour on social networks. *Proceedings of the Royal Society B: Biological Sciences*, 278(1702):42–49.

Galvani, A. P., Reluga, T. C., and Chapman, G. B. (2007). Long-standing influenza vaccination policy is in accord with individual self-interest but not with the utilitarian optimum. *Proceedings of the National Academy of Sciences*, 104(13):5692–5697.

Gelfand, M., Li, R., Stamkou, E., Pieper, D., Denison, E., Fernandez, J., Choi, V., Chatman, J., Jackson, J., and Dimant, E. (2022). Persuading republicans and democrats to comply with mask wearing: An intervention tournament. *Journal of Experimental Social Psychology*, 101:104299.

Geoffard, P.-Y. and Philipson, T. (1997). Disease eradication: private versus public vaccination. *The American Economic Review*, 87(1):222–230.

Gibbons, R. S. (1992). Game theory for applied economists. In *Game Theory for Applied Economists*. Princeton University Press.

Graeber, D., Schmidt-Petri, C., and Schröder, C. (2021). Attitudes on voluntary and mandatory vaccination against covid-19: Evidence from germany. *PloS one*, 16(5):e0248372.

Hershey, J. C., Asch, D. A., Thumasathit, T., Meszaros, J., and Waters, V. V. (1994). The roles of altruism, free riding, and bandwagoning in vaccination decisions. *Organizational behavior and human decision processes*, 59(2):177–187.

Hicks, J. R. and Allen, R. G. (1934). A reconsideration of the theory of value. part i. *Economica*, 1(1):52–76.

Hodges, B. H. (2014). Rethinking conformity and imitation: Divergence, convergence, and social understanding. *Frontiers in psychology*, 5:726.

Huang, Y. and Zhu, Q. (2022). Game-theoretic frameworks for epidemic spreading and human decision-making: A review. *Dynamic Games and Applications*, pages 1–42.

IPBES (2020). Workshop report on biodiversity and pandemics of the intergovernmental platform on biodiversity and ecosystem services.

Jevons, W. S. (1879). *The theory of political economy.* Macmillan and Company.

Jones, C., Philippon, T., and Venkateswaran, V. (2021). Optimal mitigation policies in a pandemic: Social distancing and working from home. *The Review of Financial Studies*, 34(11):5188–5223.

Kahneman, D., Slovic, S. P., Slovic, P., and Tversky, A. (1982). *Judgment under uncertainty: Heuristics and biases.* Cambridge university press.

Kahneman, D. and Tversky, A. (1979). Prospect theory: An analysis of decision under risk. *Econometrica*, 47(2):263–292.

Kanungo, R. N. and Conger, J. A. (1993). Promoting altruism as a corporate goal. *Academy of Management Perspectives*, 7(3):37–48.

Kermack, W. O. and McKendrick, A. G. (1927). A contribution to the mathematical theory of epidemics. *Proceedings of the royal society of london. Series A, Containing papers of a mathematical and physical character*, 115(772):700–721.

Kim, D. G. (2021). Vaccination lottery. *Economics Letters*, 208:110059.

Kramer, R. M. and Goldman, L. (1995). Helping the group or helping yourself? social motives and group identity in resource dilemmas. *Social dilemmas: Perspectives on individuals and groups*, pages 49–67.

Laguzet, L. and Turinici, G. (2015). Individual vaccination as nash equilibrium in a sir model with application to the 2009–2010 influenza a (h1n1) epidemic in france. *Bulletin of Mathematical Biology*, 77(10):1955–1984.

Levine, D. K. (1998). Modeling altruism and spitefulness in experiments. *Review of economic dynamics*, 1(3):593–622.

Loewenstein, G. and Thaler, R. H. (1989). Anomalies: intertemporal choice. *Journal of Economic perspectives*, 3(4):181–193.

Lyons, D. E., Young, A. G., and Keil, F. C. (2007). The hidden structure of overimitation. *Proceedings of the National Academy of Sciences*, 104(50):19751–19756.

Mandler, M. (2001). A difficult choice in preference theory: rationality implies completeness or transitivity but not both. *Varieties of practical reasoning*, pages 373–402.

Margolis, H. (1984). *Selfishness, altruism, and rationality.* University of Chicago Press.

May, R. (2000). Simple rules with complex dynamics. *Science*, 287(5453):601–602.

McAdams, D. (2020). Nash SIR: an economic-epidemiological model of strategic behavior during a viral epidemic. *Covid Economics (forthcoming).*

McMichael, A. J., Woodruff, R. E., and Hales, S. (2006). Climate change and human health: present and future risks. *The Lancet*, 367(9513):859–869.

Meppelink, C. S., Smit, E. G., Fransen, M. L., and Diviani, N. (2019). "i was right about vaccination": Confirmation bias and health literacy in online health information seeking. *Journal of health communication*, 24(2):129–140.

Monroe, K. R. (1994). A fat lady in a corset: Altruism and social theory. *American Journal of Political Science*, pages 861–893.

Myerson, R. B. (1997). *Game theory: analysis of conflict.* Harvard university press.

Nash, J. F. (1951). Non-cooperative games. *Annals of Mathematics*, 54(2):286–295.

Nichol, K. L. and Hauge, M. (1997). Influenza vaccination of healthcare workers. *Infection Control & Hospital Epidemiology*, 18(3):189–194.

Nickerson, R. S. (1998). Confirmation bias: A ubiquitous phenomenon in many guises. *Review of general psychology*, 2(2):175–220.

Nielsen, M. and Blank, C. (2011). Imitation in young children: when who gets copied is more important than what gets copied. *Developmental psychology*, 47(4):1050.

Ogawa, R. T. and Malen, B. (1991). Towards rigor in reviews of multivocal literatures: Applying the exploratory case study method. *Review of educational research*, 61(3):265–286.

Over, H. and Carpenter, M. (2012). Putting the social into social learning: explaining both selectivity and fidelity in children's copying behavior. *Journal of Comparative Psychology*, 126(2):182.

Pachetti, M., Marini, B., Benedetti, F., Giudici, F., Mauro, E., Storici, P., Masciovecchio, C., Angeletti, S., Ciccozzi, M., Gallo, R. C., et al. (2020). Emerging sars-cov-2 mutation hot spots include a novel rna-dependent-rna polymerase variant. *Journal of translational medicine*, 18(1):1–9.

Pareto, V. (1909). *Manuel d'économie politique*, volume 38. Giard & Brière.

Possajennikov, A. (2000). On the evolutionary stability of altruistic and spiteful preferences. *Journal of Economic Behavior & Organization*, 42(1):125–129.

Ramsey, F. P. (1926). Truth and probability. In Braithwaite, R. B., editor, *The Foundations of Mathematics and other Logical Essays*, chapter 7, pages 156–198. McMaster University Archive for the History of Economic Thought.

Randolph, J. (2009). A guide to writing the dissertation literature review. *Practical Assessment, Research, and Evaluation*, 14(1):13.

Reñosa, M. D. C., Landicho, J., Wachinger, J., Dalglish, S. L., Bärnighausen, K., Bärnighausen, T., and McMahon, S. A. (2021). Nudging toward vaccination: a systematic review. *BMJ global health*, 6(9):e006237.

Ritov, I. and Baron, J. (1990). Reluctance to vaccinate: Omission bias and ambiguity. *Journal of behavioral decision making*, 3(4):263–277.

Samuelson, P. A. (1938). A note on the pure theory of consumer's behaviour. *Economica*, 5(17):61–71.

Schein, E. H. (1954). The effect of reward on adult imitative behavior. *The Journal of Abnormal and Social Psychology*, 49(3):389.

Schlag, K. H. (1998). Why imitate, and if so, how?: A boundedly rational approach to multi-armed bandits. *Journal of economic theory*, 78(1):130–156.

Schlag, K. H. (1999). Which one should i imitate? *Journal of Mathematical Economics*, 31(4):493–522.

Scott, J. and Trubek, D. M. (2002). Mind the gap: law and new approaches to governance in the european union. *European Law Journal*, 8(1):1–18.

Segal, U. and Sobel, J. (2007). Tit for tat: Foundations of preferences for reciprocity in strategic settings. *Journal of Economic Theory*, 136(1):197–216.

Selten, R. (1998). Features of experimentally observed bounded rationality. *European Economic Review*, 42(3-5):413–436.

Selten, R. and Ostman, A. (2001). Imitation equilibrium. *Homo Oeconomicus*, 43:111–149.

Sen, A. (1969). Quasi-transitivity, rational choice and collective decisions. *The Review of Economic Studies*, 36(3):381–393.

Sendi, P., Locher, R., Bucheli, B., and Battegay, M. (2004). The decision to get vaccinated against influenza. *The American journal of medicine*, 116(12):856–858.

Shim, E., Chapman, G. B., Townsend, J. P., and Galvani, A. P. (2012). The influence of altruism on influenza vaccination decisions. *Journal of The Royal Society Interface*, 9(74):2234–2243.

Simon, H. A. (1957). Models of man; social and rational.

Simpson, B. (2006). Social identity and cooperation in social dilemmas. *Rationality and society*, 18(4):443–470.

Spranca, M., Minsk, E., and Baron, J. (1991). Omission and commission in judgment and choice. *Journal of experimental social psychology*, 27(1):76–105.

Stahl, D. O. and Wilson, P. W. (1995). On players models of other players: Theory and experimental evidence. *Games and Economic Behavior*, 10(1):218–254.

Stone, L., Shulgin, B., and Agur, Z. (2000). Theoretical examination of the pulse vaccination policy in the SIR epidemic model. *Mathematical and computer modelling*, 31(4-5):207–215.

Tajfel, H. (1972). Social categorization, english manuscript of la catégorization sociale. *Introduction à la psychologie sociale*, 1.

Tajfel, H., Billig, M. G., Bundy, R. P., and Flament, C. (1971). Social categorization and intergroup behaviour. *European journal of social psychology*, 1(2):149–178.

Tajfel, H. and Turner, J. (1986). The social identity theory of intergroup behavior. In Worchel, S. and Austin, W. G., editors, *Psychology of Intergroup Behavior*. Nelson Hall, Chicago, IL.

Thaler, R. (1985). Mental accounting and consumer choice. *Marketing science*, 4(3):199–214.

Tsutsui, Y., Benzion, U., Shahrabani, S., and Din, G. Y. (2010). A policy to promote influenza vaccination: a behavioral economic approach. *Health policy*, 97(2-3):238–249.

Turner, J. C. (1999). Some current issues in research on social identity and self-categorization theories. *Social identity: Context, commitment, content*, 3(1):6–34.

Tversky, A. and Kahneman, D. (1974). Judgment under uncertainty: Heuristics and biases: Biases in judgments reveal some heuristics of thinking under uncertainty. *science*, 185(4157):1124–1131.

Tversky, A. and Kahneman, D. (1985). The framing of decisions and the psychology of choice. In *Behavioral decision making*, pages 25–41. Springer.

Tversky, A. and Kahneman, D. (1991). Loss aversion in riskless choice: A reference-dependent model. *The quarterly journal of economics*, 106(4):1039–1061.

Tversky, A. and Kahneman, D. (1992). Advances in prospect theory: Cumulative representation of uncertainty. *Journal of Risk and uncertainty*, 5(4):297–323.

Vega-Redondo, F. (1997). The evolution of walrasian behavior. *Econometrica: Journal of the Econometric Society*, pages 375–384.

von Neumann, J. and Morgenstern, O. (1944). *Theory of games and economic behavior*. Princeton University Press. (1st ed.).

von Neumann, J. and Morgenstern, O. (1953). *Theory of games and economic behavior*. Princeton University Press. (3d ed.).

Wakker, P. and Tversky, A. (1993). An axiomatization of cumulative prospect theory. *Journal of risk and uncertainty*, 7(2):147–175.

Wein, T. (2021). Ist eine Impfpflicht gegen das Coronavirus nötig? . *Wirtschaftsdienst*, 101:114–120.

Xia, S. and Liu, J. (2013). A computational approach to characterizing the impact of social influence on individuals' vaccination decision making. *PloS one*, 8(4):e60373.

Yamagishi, T. and Mifune, N. (2008). Does shared group membership promote altruism? fear, greed, and reputation. *Rationality and Society*, 20(1):5–30.

Statutory Declaration

I promise, that I wrote my thesis by myself and that I didn't use other references or auxiliary aids, which I didn't quote. Every passage, which I took word by word or analogous out of other sources, have been marked properly. The work or an similar work was not handed before at another examination office.

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