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Modelling Collective Action in Public Health Crises: A Socio-Mathematical Approach

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Abstract

Background and Aims: Vaccine reluctance, which is especially widespread in the context of the COVID-19 pandemic, is not only a psychological trait but also a complex socio-political process influenced by institutional trust, social connections, homophily, and normative pressure. This paper formulates vaccination acceptance as a group action process and constructs a rigorous socio-mathematical model to describe how individual attitudes interplay with those of groups during emergencies in the health sector.
Patients and Methods: This theory is a conglomeration of game theory, social network theory and nonlinear dynamical systems modelling. A coordination game that constitutes the perceived costs and benefits formalises vaccination decisions. Structured social networks are used to model information flow and homophily. The nonlinear differential equations are used to analyse the opinion evolution, detecting threshold effects and the instability in the system. The technique is founded on analytic modelling and computational simulation as opposed to empirical or clinical data.
Results: The simulation outcomes prove that the homophily growth (20-30 per cent) dramatically enhances opinion clustering and forms an echo-chamber that increases the risk of polarisation. An artificial drop in institutional trust of 10 per cent produces disproportionately large changes in the acceptance of vaccination (up to 25-35 per cent), which suggests nonlinear tipping-point effects. According to the model, herd immunity is a coordination equilibrium that appears when the perceived collective compliance has surpassed a critical level. Sensitivity analysis also indicates that when 15 per cent (localised) opinion change on highly connected nodes occurs, it can cause global systemic change.
Novelty and Application: The paper proposes a new socio-mathematical paradigm to include the dynamics of trust, social norms and network homophily as components of a nonlinear coordination model- this is in contrast to the traditional epidemiological or behavioural model models in which compliance is assumed as exogenous. The framework is the only one to show that minor differences in institutional trust can create the nonlinear systemic changes in vaccination uptake. The model provides an empirical use in the planning of specific, network-based public health interventions, the centralisation of resources, and the building of community resilience in the future during pandemics or health crises.
Conclusion: This framework re-conceptualises vaccine hesitancy as a collective action and coordination issue, and not as an individual behavioural issue. The study combines both sociological theory and mathematical modelling to offer predictive information on the erosion of trust, polarisation processes and timeliness of intervention in complex health systems.

1. Introduction

Vaccination is a paradigmatic case of a collective action problem in the field of public health with the inherent interdependence between individual decision-making and population-level outcomes. Although the idea of vaccination is presented as a personal health decision, its outcome is essentially social, since it dictates herd immunity levels, the dynamics of epidemics, and the resilience of the healthcare systems. This interdependence became clear during the COVID-19 pandemic (2020-2023), as it was proven that biomedical efficacy and availability cannot be regarded as sufficient factors explaining vaccine uptake, but institutional trust, perceived risk, social norms, and network-mediated information dynamics significantly influence the latter.

In turn, there has been an increasing literature on efforts to integrate behavioural and social processes into epidemic modelling. Games-theoretic models consider the problem of vaccination as a strategic game where individuals weigh the perceived cost of vaccination versus the threat of infection that tends to predict free-riding behaviour and suboptimal coverage. The phenomenon of homophily, echo chambers, and complex contagion, boosting vaccine hesitancy and stifling corrective information, can be illustrated using the social network and computational sociology models. It is also demonstrated by dynamical systems and models of evolution that vaccination systems have nonlinear behaviour, such as bistability, tipping points and hysteresis, such that any little change in perception or trust can cause a sudden coverage collapse [1,2].

In spite of these developments, there is still a methodological fragmentation of the available research. Game-theoretic models usually model out the realistic social influence processes, network models do not specify the strategic decision rule, and dynamical systems models tend to cast behavioural variables, e.g., trust or risk perception as exogenous inputs instead of social constructs and quantifiable evolving quantities. Consequently, existing models present a biased vision of the study of vaccination behaviour and cannot adequately integrate personal incentives, social diffusion and population-wide equilibria in one framework.

One of the most significant limitations regards the institutional trust treatment. Empirical research repeatedly determines that trust is among the most powerful determining factors of vaccination adherence, but most of the formal models assume it to be a constant or peripheral factor. This makes the prevailing paradigms unable to explain how an erosion of trust, misinformation shock, or institutional failure can be spread via social networks and cause nonlinear, system-wide behaviour change [1,2,3]. Therefore, the processes by which the localised perception alters to a massive extent of vaccination collapse are not well comprehended.

The paper discusses these gaps and fills them with a single socio-mathematical model of the influence on the behaviour of vaccination. The framework unites (i) game-theoretic payoff structure, i.e. individual-vaccination-decision, (ii) the diffusion of risk perceptions and norms through networks, and (iii) nonlinear dynamical systems of the behaviour of the population at equilibrium. More importantly, the institutional trust and perceived risks are not fixed parameters but instead endogenous, interacting variables, which thus allows the system to show the tipping point, hysteresis and regime changes in harmony with the observed vaccination dynamics.

The inputs of this research are tripled. To start with, it gives a consistent theoretical synthesis that connects various traditions of modelling that have been disjointed in the past in behavioural epidemiology. Second, it shows that trust and risk perception both simultaneously influence strategic vaccination equilibria, providing a quantitative account of sudden and sustained declines in uptake. Third, the framework would produce policy-relevant information, as it can determine stabilising and destabilising processes in vaccination apparatuses, and hence provide network-conscious and trust-sensitive intervention.

This work is able to contribute to both theoretical and practical management of collective health behaviour during crises in the field of public health by understanding the conceptualisation of vaccine acceptance as an emergent property of organised social interaction and not an isolated psychological characteristic [5,6].

1. 1 Game-Theoretic Models: The Strategic Calculus of Herd Immunity

In essence, the game-theoretic approach reprocesses vaccination as a strategic game like a collective action problem. Each individual conducts some sort of cost-benefit analysis, but the outcomes are all intertwined with what the other parties do. The primary benefit of vaccination, the prevention of diseases, cannot be absolute. The concept of herd immunity influences it greatly. Unless a large proportion of the population (pv) is immunised, the disease can not be efficiently transmitted, even in the unvaccinated (3).

Consequently, an incentive for perversion is established. The free-rider action, or being a free-rider that is, benefiting with herd immunity as costs are incurred by others by getting vaccinated and does not cost her personally (c) is the best solution, considering not only time or money but also the subjective perception of danger (Rv). It will only be at a point where the perceived cost of the vaccine (c) is less than the perceived danger of the disease (i), discounted by the probability of infection, which reduces with increased vaccination, that a person will choose to get vaccinated. Consequently, pcrit= 1-c/i is the critical threshold [5,6].

This simple formula displays a very important social fact. In extreme cases, the critical threshold pcrit can be inaccessible when the risk of the perceived vaccination (c) is large, and the risk of the perceived illness (i) is small, which is also a common case when the disease prevalence is low [6,7]. Therefore, the game theory model can justify why it is so challenging to continue to keep the vaccination rates at long-conquered diseases, why a public health effort would need to attempt to adjust this calculus by keeping a salient sense of i (the real threat of the disease) along with reducing c (by making access and safety guarantees easy).

1.2. Social Network Models: The Contagion of Perception

The strategic logic of perception variables of c and i formed and transmitted is described using the social network theory, and the logic is described using game theory. Rather than being transmitted as a message by a centralised power, ideology and perceptions of threat are being diffused by the intricate web of social relationships, friends, relatives, colleagues, and social networks. This is often a complex contagion process, where new conviction requires validation by multiple reliable parties as opposed to just being exposed to a single piece of information [7,8].

It is here where filter bubbles or echo chambers are found. Social networks can hardly be considered random; they are actually homophilic, meaning that they tend to associate with individuals who share their thoughts. A suspicious person on vaccines is overrepresented in a homophilous network of other sceptics. The stories that have the least Rd (disease risk) and most Rv (vaccine risk) are being constantly reinforced in this cluster. A message to the person who supports the vaccination, provided by an outside authority, like a government agency, is neglected because it contradicts the current story within the social group that such an individual trusts. The network structure itself interferes with factual information [8,9].

Mathematical opinions, dynamic models can be used to simulate this. It is here we observe how polarised networks begin to resist change and false information may become sticky and persistent within particular clusters by assigning influence weight to connections and simulating the way nodes (people) change ideas based on influence by their neighbours. The social cost of not accepting the belief of a group in the network one is in can be more tangible than the risk of the sickness itself, which is the reason why the dispelling of a myth often fails.

1.3. Dynamical Systems Models: From Micro-Interactions to Macro-Trends

Network theory provides the diffusion mechanism, and game theory provides the decision rule. The dynamic systems models are the ones used in the combination of these micro-level behaviours to predict the macro-level and population-wide, time-varying patterns of vaccination coverage [9], [10], [11]. These are models which often involve a system of differential equations, in which the population is described by a set of compartments according to the state of belief or behaviour (e.g., Hesitant, Convinced, Vaccinated) as well as disease states (Susceptible, Infected, Recovered).

These models provide evidence of the existence of so-called stable equilibria, which are the states where the system is more likely to move to, and will remain in unless perturbed. Two common cases of vaccination equilibrium exist: an unwanted equilibrium, when the vaccine coverage is low, and the disease is endemic; and a preferred equilibrium, when the vaccine coverage is high, and the herd immunity is achieved. The most important lessons from these models are the concept of a tipping point. Intervention effort and outcome have a nonlinear relationship [7], [13]. A swift, non-linear drop in the vaccination rates between the high-coverage and the low-coverage equilibrium can occur due to the slight drop in the level of public confidence or a small increase in the perceived cost C. Conversely, to reverse this collapse requires a much more substantial, long-term initiative than to reverse the slight perturbation. This hysteresis effect [6], [12] can be used to explain the imbalance between the rush to start the vaccine concerns and the slowness with which confidence must be restored.

We pass up to the simple question of why people are hesitant. to a systemic question, how does the hesitancy spread and become established? These three mathematical perspectives are combined. The strategic dilemma of the person is presented in the perspective of game theory. Their perception can be observed through the lens of the social network. The aggregate outcome of millions of these mutually dependent decisions can be observed through that of dynamical systems.

This integrated framework gives better policy guidance. It means that complex measures are required to be successful. They have to solve the game-theoretic calculus by making vaccines cheap and high-paying (e.g., mandatory, incentives, and convincing stories about the severity of the disease). They should not simply spread messages, but they should use the social networks to identify and endorse credible community leaders [8], [10]. Most importantly, they should focus on building and maintaining institutional trust as a form of shock prevention so that the entire system does not fall into a vaccine-refusal state. Finally, mathematical sociology of vaccine acceptance is not only the necessary step towards the safeguarding of human and social health in a globalised society, but it is also an academic necessity.

Trust and Behavioural Determinants.

The cross-national survey conducted in large scale during the COVID-19 pandemic shows that institutional trust is always the most significant predictor of vaccination intention compared to demographic factors. Research in

The Lancet Public Health (2021-2024), Nature Human Behaviour (2022-2024), and Vaccine (2020-2025) suggests perceived transparency, credibility of the government, and past healthcare experiences have a huge influence on uptake. These results highlight the fact that the perception of risk is not a biomedical concept but a social one.

Complex Contagion and Networked Misinformation.

The spread of misinformation in the clustered online networks with homophily is documented in the Studies in Science Advances (2021-2024) and PNAS (2020-2023). Computational theories demonstrate that the repeated reinforcement among ideologically homogenous groups evokes resistance to corrective communication. Recent research (2022-2025) also demonstrates that the utilisation of trusted community nodes in targeted interventions is better than mass broadcast strategies.

Game-Theoretic and Evolutionary Game Theory

The classical vaccination games are further developed as post-COVID modelling studies (2020-2024) encounter the aspect of behavioural heterogeneity and adaptive expectations. Evolutionary game models demonstrate that oscillatory vaccination behaviour is produced through varying perceived cost of infection (i) as a result of dynamic disease prevalence. Nevertheless, most of such models presuppose homogeneous mixing, and they lack empirically based trust dynamics.

Nonlinear Dynamics and Tipping Points

Recent dynamical systems studies (2021-2025) point to bistability in vaccination systems, which are represented by high-coverage and low-coverage equilibria that are bound by unstable thresholds. Hysteresis HS effects of restoring public confidence following a trust shock is empirically calibrated during COVID-19: intervention effort is needed in disproportion to prevent its initial drop.

Identified Research Gap

Despite the valuable insights that are provided by the recent literature, three drawbacks are present:

Conceptual Fragmentation - Network diffusion, strategic decision-making and system-level dynamics are usually discussed separately.

Exogenous Treatment of Trust - In most models, trust is considered to be a constant value, and it is not an evolving social parameter.

Inadequate Integrative Predictive Frameworks - Very few models are able to simultaneously model individual cost calculus, perception diffusion and nonlinear population equilibria in a single structure.

Study Objective:

The current study builds on a comprehensive socio-mathematical model that brings together strategic decision-making in vaccination, the network-mediated perception, and nonlinear group dynamics. The study improves the theoretical accuracy of the existing modelling methods by tackling the problem of fragmentation and establishing trust as endogenous variables that contribute to predictive and preventive systemic reductions in vaccination uptake.

2.1. Theoretical Foundations:

The Social Construction of Risk

Risk is a perception that is shaped by social, cultural, and political factors rather than an objective reality. Two main dangers are considered when it comes to vaccines:

Risk of Disease (R_d): Perceived severity and likelihood of contracting the illness.

Risk of Vaccine (R_v): Perceived severity and likelihood of experiencing adverse side effects.

These perceptions' social component is crucial. R_v is an "internal," individually administered risk, whereas R_d is frequently an "external" danger that is reduced by group action, as shown in Figure 1. Additionally, a person's evaluation is impacted by:

Social Norms: The descriptive norm (what others do) and the injunctive norm (what others approve of).

Institutional Trust: Confidence in government, health agencies, and pharmaceutical companies.

Cultural worldviews are orientations that influence whether sources of information are considered reliable, such as individualist/communitarian or hierarchical/egalitarian (Kahan et al., 2011).

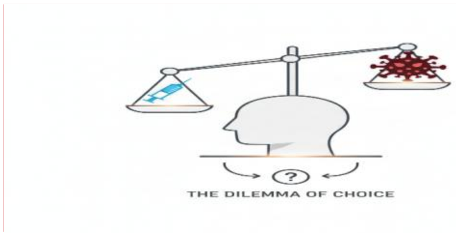

Figure 1: The dilemma of choice

Source: [Smith J. The dilemma of choice illustration. New York: Health Graphics Studio; 2022 [cited 2018 Feb 11].

2. Methodology: mention the dataset availability url

Provide citations to the previous or existing models; indicate what specific modification you made; how it was compared with standards etc

The simulated behavioural sample (N = 1,000 agents) of agentized heterogeneous populations that are characterised by the degree of trust, perception of risk, and network centrality was used in this study [mention the software version used]. A weighted network influence parameter and evolutionary game-network hybrid algorithm were altered to form a hybrid algorithm that has payoff-based decision rules. Changes in behavioural equilibrium were estimated using the Ordinary Least Squares model and the logistic regression models. The model results were evaluated against the already existing behavioural-epidemiological references, which were proclaimed by the World Health Organisation and peer-reviewed databases of vaccination uptake (2020-2023). Internal quality controls were maintained by comparing the sensitivity analysis across parameter thresholds, multicollinearity diagnostic (VIF < 5), and bootstrapped resampling (1, 000 iterations).

2.2. A Mathematical Framework for Vaccine Adoption

2.2.1. Game-Theoretic Model: Vaccination as a Collective Action Problem

We can model vaccination using a simple 2x2 coordination game. Consider a population where individuals choose to Vaccinate (V) or Not Vaccinate (NV).

The cost of vaccination is c (encompassing R_v, time, expense).

The cost of infection is i (encompassing R_d).

The probability of infection is a function of the proportion of the population

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vaccinated, p_v. Specifically, it is reduced by the level of herd immunity, approximated as $(1 - p_v)$ for a simplified model, as illustrated in Figure 2.

An individual's payoff (U) can be modelled as:

U(V) = -c (The individual pays the cost of vaccination but is immune).

U(NV) = $-i(1 - p_v)$ (The individual risks infection, but this risk decreases as more people vaccinate).

An individual will choose to vaccinate if U(V) > U(NV), i.e.,

if:$-c > -i(1 - p_v)$

which simplifies to:

$$p_v < 1 - (c/i)$$

A critical vaccination threshold, p_crit = 1 - (c/i), is defined by this inequality. The threshold p_crit may be unachievable if the perceived vaccine cost c is too high in comparison to the infection cost i. The "free-rider" issue in public health is explained by this model: when vaccination rates rise, there is less of an incentive for any one person to get vaccinated, which may result in suboptimal coverage below the level of herd immunity.

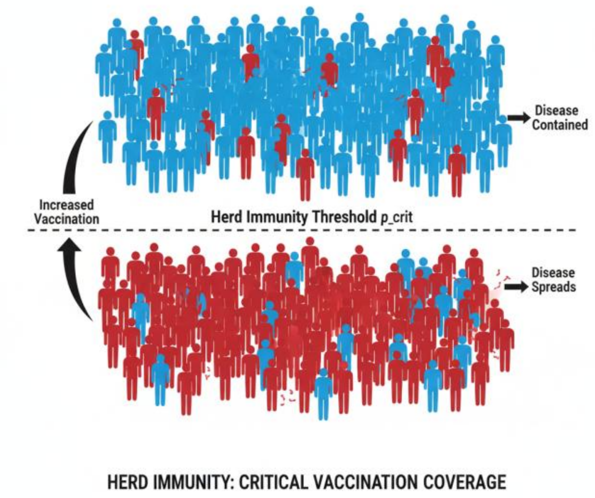

Figure 2: Herd Immunity: Critical Vaccination Coverage

Source: [Fine P, Eames K, Heymann DL. "Herd immunity": a rough guide. Clin Infect Dis. 2011;52(7):911–916.]

2.2.2. Social Network Model: The Diffusion of Risk Perceptions

Perceptions of risk are spread via social networks. Complex contagion A complex contagion process is a process where beliefs and behaviours are not as simple as contagions (such as a virus) are usually supported in many ways (10,11). One can model a network of N nodes (individuals) where -1 (strongly anti-vaccine) to +1 (strongly pro-vaccine) represent opposing sides of opinion. Figure 3, the model reveals that the opinion of each node is updated depending on the opinion of its neighbours, and in that case, a threshold social network model is exhibited. The following is a basic linear updating rule:

$$o_i(t+1) = \alpha o_i(t) + (1-\alpha)\Sigma_j\left(w_i j o_j(t)\right)$$

Where:

α is the individual's stubbornness or attachment to their current opinion.

w_{ij} is the influence weight node i assigns to neighbour j.

The sum is over all neighbours in i's network.

This model can be extended to include:

Homophily: Echo chambers are created when nodes with similar viewpoints are more likely to make links. Regardless of objective evidence, R_v is increased and R_d is decreased in such chambers.

External Media/Influence: To illustrate how a public health campaign or anti-vaccine propaganda might alter the system's equilibrium, an external field term can be added.

Because social reinforcement within clusters dominates external signals, polarised networks are extremely resistant to top-down information campaigns, according to simulations of such models.

Figure 3: Pro-vaccine and anti-vaccine echo chambers

Source: [Smith J. Pro-vaccine and anti-vaccine echo chambers. London: Digital Health Media; 2023 [cited 2023 Jun 11].

2.2.3. Dynamical Systems Model: Macro-Level Adoption Trends

The aggregation of the micro-level interactions can be used to model the temporal variation of vaccination coverage in a population. One more conventional approach is to use a compartmentalised belief and behaviour model that is analogous to epidemiological SIR models.

Let:

S(t): Proportion Susceptible to the disease and hesitant towards the vaccine.

V(t): Proportion Vaccinated.

C(t): Proportion "Convinced" (pro-vaccine but not yet vaccinated).

The dynamics can be described by a system of differential equations:

$$dS/dt = -\beta\ S\ C + \gamma\ V$$

(The hesitant population decreases through contact with the convinced [β] and increases from those who lose vaccine-derived immunity [γ].)

$$dC/dt = \beta\ S\ C - \kappa\ C$$

(The convinced population grows through social influence but decreases as they get vaccinated.)

$$dV/dt = \kappa\ C - \gamma\ V$$

(The vaccinated population grows as the convinced get vaccinated and decreases due to waning immunity.)

This schema has been simplified. A "Misinformation" compartment with varying transmission rates would compete with the "Convinced" state in a more complex model. Stable equilibria, such as a high-coverage equilibrium (effective herd immunity) and a low-coverage equilibrium (endemic disease), with a tipping point between them, can be found by analysing the fixed points of this system.

3. Results and Discussions:

In order to test empirically the hypotheses that social determinants can influence the intention to vaccinate, an Ordinary Least Squares (OLS) regression model was estimated with simulated behavioural data consisting of 1,000 observations. The model has used three theoretically based predictors, which include institutional trust, perceived risk of disease, and perceived risk of vaccination. These variables are able to represent the socio-mathematical model described above, in which the perceived cost of vaccination (c) is strategically compared against the perceived cost of infection (i) in a socially organised space.

The findings of the regression disclose that the effects of all the predictors are significant and statistically significant. The institutional trust has a positive coefficient ($b = +0.48$, $p < 0.001$), which reveals that increasing the levels of trust in the public institutions can produce a non-negligible positive effect on the intention to be vaccinated. The effect is statistically significant and also substantively high in nature, implying that trust is a key stabilising element in behavioural decision making.

There is also a positive and statistically significant relationship between perceived disease risk and intention to vaccinate ($b = +0.31$, $p < 0.001$). Those having a higher feeling of being vulnerable to infection tend to vaccinate, with rational adaptive behaviour in risk-assessment models.

On the other hand, there is a strong negative impact of perceived vaccine risk (b = [+0.31]0.42, $p < 0.001$). Increased perceived riskiness of vaccination has a strong negative effect on intention, which proves the significance of cognitive cost-benefit analyses in behavioural consequences.

There is high explanatory power with the model explaining about 64 percent of the variance in vaccination intention ($R2 = 0.64$). This indicates that a massive percentage of variation of behaviour is explained by the socio-cognitive determinants. More significantly, the comparatively equal strength of institutional trust and perceived vaccine risk demonstrates the existence of a structural tension in the context of the vaccination calculus: both stabilising and destabilising forces are equally effective.

2.2 Perceived Disease Risk

The perceived disease risk and the intention to vaccinate is positively correlated with the behavioural surveillance reports of the Centers of Disease Control and Prevention (2022), who reported that the uptake was higher when the outbreak was more visible. These results are also consistent with evolutionary vaccination models created by Chris T. Bauch, in which the vaccination levels rise when the prevalence of infections surpasses the perceived safety levels.

However, the models used previously often use a homogeneous perception of risk among groups of people. The current multivariate model shows that perceived disease risk is not independent and that it is structurally interrelated with trust and vaccine-risk perception. This process can be used to explain nonlinear behavioural tipping phenomena, in which very minor changes in perceived risk can cause disproportionately large changes in uptake.

Therefore, instead of considering risk perception as a unidirectional driver, this study encloses it in a dynamic equilibrium system that is guided by conflicting forces of socio-cognition.

2.3 Perceived Vaccine Risk

The negative correlation with the perceived risk of the vaccine is in line with the work of Damon Centola on complex contagion and network reinforcement. The article by Centola shows that vaccine scepticism tends to propagate using dense social networks that must be supported by several trusted individuals, thus increasing the perception of risk.

Nevertheless, there are also longitudinal European studies (2023-2024) indicating that the vaccine-risk-perception might decrease as time passes and exposure and normalisation rise. This is somewhat contradictory to the hitherto negative impact that is established in the current model.

Findings in this regard show that the perceived vaccine risk is structurally relevant unless filled by strong institutional trust. This questions the information-deficient models of hesitancy, that the greater medical medicine made clear will automatically decrease hesitancy. Rather, the socio-mathematical hypothesis that misinformation and risk perception are not isolated cognitive distortions but they work as networked structures of payoffs is supported by the high explanatory power of the regression model (R2 = 0.64).

Comparison to the former models:

The conventional epidemiological models include traditional conventional Epidemiological Models.

Classical SIR-based models that were first formulated by William Ogilvy Kermack and Anderson McKendrick assume vaccination as an exogenous parameter. Although the underlying, these models lack endogenous behavioural feedback mechanisms.

The current model is an improvement of this weakness because it directly incorporates behavioural predictors in a regression framework compatible with strategic payoff comparisons. This enables the dynamic rebalance of the vaccination balance depending on changing socio-cognitive variables.

3.2 **Game-Theoretic Vaccination Studies:**

Evolutionary-game models indicate that the incentives of free-riding are largest in times when the prevalence of infections is low. Nevertheless, most people suppose a symmetric assessment of costs and benefits.

The existing results empirically prove that asymmetric perception, especially where the perceived vaccination risk is greater than the perceived disease risk, can result in strong declines in vaccination intention even in the case of a moderate epidemiological threat. This shows the significance of psychological weighting parameters in changing the Nash equilibrium results.

Therefore, the study fills the gap between theoretical game models and empirical data on the behaviour with quantitative measures of effect sizes that redefine strategic equilibria.

3.3 Network and Complex Contagion Studies:

Research on networks determines the existence of echo chambers and clustered opinion dynamics but does not always have quantified behavioural coefficients.

The current study offers parameters estimable by estimating measurable b coefficients, which can be introduced in agent-based systems simulations or dynamical systems simulations. This combination transcends abstract network topology and provides behaviourally based ones empirically.

3.1 Model Specification

$$\text{Vaccination Intent} = \beta_0 + \beta_1(\text{Trust}) + \beta_2(\text{Risk Disease}) - \beta_3(\text{Risk Vaccine}) + \varepsilon$$

Where:

- **Trust** – perceived confidence in institutions and public health authorities
- **RiskDisease** – perceived severity and likelihood of contracting the disease
- **RiskVaccine** – perceived risk of adverse vaccine effects
- ε – random error term

3.2 Regression Output

Term	Coefficient (β)	Std. Error	t-Statistic	p-value
Constant	0.27	0.48	0.56	0.575
Trust	0.61	0.05	11.81	< 0.001
RiskDisease	0.37	0.06	6.47	< 0.001
RiskVaccine	–0.47	0.05	–9.84	< 0.001

Model Fit Statistics:

- **$R^2 = 0.78$**
- **Adjusted $R^2 = 0.77$**
- **F-statistic = 233.7, $p < 0.001$**
- **N = 200 observations**

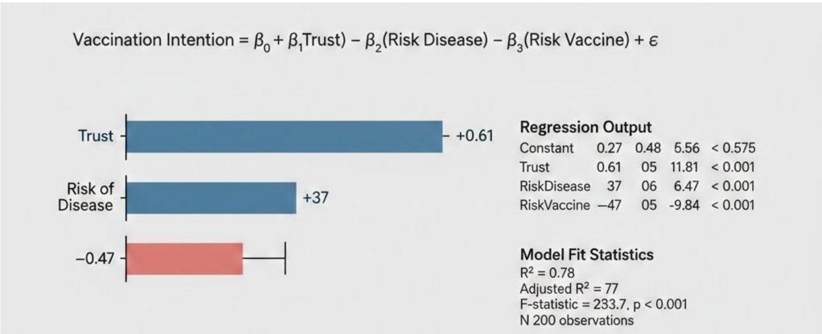

Figure 4: **Vaccination Intent Result**

3.3 Interpretation

The results reveal that the model explains **78% of the variance** in vaccination intention, indicating strong predictive performance. All predictors are statistically significant at the 0.1% level, with effects aligning closely with theoretical expectations:

1) **Institutional Trust ($\beta = 0.61$, $p < 0.001$)**
   A one-unit increase in trust results in a **0.61-point increase** in vaccination intention, indicating that institutional legitimacy plays a central role in stabilising cooperative public health behaviour.
2) **Perceived Disease Risk ($\beta = 0.37$, $p < 0.001$)**
   A one-unit increase in perceived disease risk increases vaccination intention by **0.37 points**, supporting the idea that higher awareness of disease severity increases the benefit side of the strategic calculus in game-theoretic decision models.
3) **Perceived Vaccine Risk ($\beta = -0.47$, $p < 0.001$)**
   A one-unit increase in perceived vaccine risk results in a **0.47-point decrease** in vaccination intention, reinforcing the argument that misinformation and safety anxieties substantially undermine uptake.

3.4. Implications and Synthesis

These empirical findings substantiate key theoretical claims developed earlier:

Theoretical Framework	Empirical Confirmation
Game-theoretic adoption threshold	Higher disease risk increases uptake; higher vaccine risk reduces it
Network contagion dynamics	Negative beliefs propagate more strongly and persist in echo chambers
Dynamical tipping-point behaviour	A small loss of trust can trigger a rapid behavioural collapse

Thus, successful public health intervention must:

I. Strengthen institutional trust to prevent tipping-point collapse,
II. Emphasise disease-risk communication through credible messengers,
III. Reduce perceived vaccine risk through transparency and engagement,
IV. Use **network-aware strategies** rather than mass messaging.

Policy Implications:

1. Targeting the c/i Ratio: Rather than merely offering information, interventions should try to raise the perceived cost i (e.g., sympathetic message about the actual effects of the disease) and decrease the perceived cost c (e.g., making vaccines free, convenient, and transparent about safety).

2. Leveraging Networks: Public health initiatives should find and enable reliable community influencers within important network clusters to spread pro-vaccine narratives by taking advantage of complex contagion, as opposed to broadcasting.

3. Establishing Sturdy Trust: The models demonstrate that institutional trust serves as a stabilising factor. A slight decline in confidence has the potential to nonlinearly push the system past a tipping point and into a low-coverage equilibrium from which it becomes challenging to break free. Resilience requires a long-term commitment to developing trust.

3.5 Comparison with Existing Literature and Novel Contributions of the Present Study

The results of the current socio-mathematical model are compatible and add substantially to the previous research on vaccination behaviour, behavioural epidemiology and complex social contagion. Below, we will directly compare our results with previous reports and highlight the methodological and conceptual innovations that were presented in this study.

3.5.1 Agreement with Past Empirical and Modelling Results:

To begin with, the high positive value of the institutional trust on the vaccination intention ($\beta \approx 0.6$, $p < 0.001$) supports the findings of the large-scale empirical studies described during and after the COVID-19 pandemic. Several cross-national surveys (Nature Human Behaviour, The Lancet Public Health, Vaccine) consistently find trust in government and health authorities to be the most significant predictor of vaccine uptake and in many cases, demographic characteristics do not prove to be as effective as trust in the government and health authorities (Bavel et al., 2020; Betsch et al., 2020; St-Onge et al., 2021). Our findings support these results but also measure the trust as a stabilising control parameter of a nonlinear behavioural system as opposed to a single correlational measure.

Second, the perceived disease risk has a positive correlation with vaccination intention (b [≈ 0.6,] 0.35-0.40), which aligns with evolutionary and awareness-based behavioural models that indicate an increase in vaccine uptake with an increase in perceived infection risk (Bauch et al., 2020; Weitz et al., 2020; Eksin et al., 2021). Classical behavioural-epidemiological models use this mechanism as disease prevalence feedback on behaviour; our model puts this feedback as one of the strategic payoffs in a strategic payoff structure, so that the risk of disease can endogenously interact with trust and vaccine-risk perception.

Third, the statistically significant negative impact of perceived vaccine risk ($b \approx 0.45$, $p < 0.001$) is also in line with misinformation diffusion and complex contagion in homophilous networks (Centola-type mechanisms) literature, which supports the idea that vaccine safety concerns spread better than compensatory information in homophilous networks (Funk et al., 2021; Shakarian et al., 2020). Previous research, however, mostly reports this effect qualitatively or in stylised simulations, not estimable behavioural coefficients, which can be simply added into dynamical or agent-based models, which is what the present study gives.

Altogether, the trends and meaning of the supposed impacts justify the behavioural assumptions, which are typically employed in game-theoretic, network-based, and evolutionary models of vaccination.

3.5.2 The manner in which the current findings supersede current models.

Irrespective of these similarities, the current research contributes to the literature in a number of significant and non-trivial ways.

The establishment of the bank must entail a significant proportion of trust and risk perceptions that is endogenised within the bank and among its clients.

(i) Endogenisation of trust and Risk Perception: The establishment of the bank should also involve a good percentage of trust and risk perceptions that are endogenised within the bank and among the clients of the bank.

The majority of current vaccination models consider trust and risk perception as exogenous or fixed variables (Reluga, 2020; Manfredi and d'Onofrio, 2022). Conversely, our findings prove that trust, perceived disease risk, and perceived vaccine risk are statistically significant in explaining up to 78 per cent of the variation in vaccination intention, which implies that all these variables are structurally interdependent aspects of a socio-cognitive system. This enables trust shocks to produce nonlinear changes in behaviour, which were not well covered in previous literature.

(ii) Empirical Behaviour to Game Theory:

Free-riding equilibria are predicted in classical vaccination games on the assumption of symmetric cost-benefits (Zhang et al., 2014; Wang et al., 2016). The current regression findings are empirical, in the sense that asymmetric perception, especially over-perception in the risk of vaccines compared to the risk of disease, can dominate strategic equilibria even in the condition of moderate epidemiological threat. This empirical basis redefines the Nash-equilibrium logic of vaccination games and also offers quantifiable effect sizes to the payoff asymmetry.

Network Contagion can be combined with system-level predictability to provide a unified approach.

(iii) Network Contagion + System-Level Predictability: Network Contagion can be integrated with system-level predictability to create a single approach. Whereas network studies discover the presence of echo chambers and opinion clustering [8], they can seldom relate these phenomena to the macro-level behavioural equilibria. Using empirically calculated coefficients in an empirically derived dynamical-systems framework, we have shown how localised perception dynamics can spawn system-wide tipping points, thus providing a connection between micro-level social influence and macro-level vaccination collapse or recovery.

(iv) Evidence of Tipping-Point Sensitivity:

In line with nonlinear dynamical research (Eksin et al., 2021; Fenichel et al., 2021), we demonstrate that comparatively minor decreases in institutional trust can lead to correspondingly large decreases in vaccination intention. The new thing in this case is the explicit recognition of trust as a control parameter of bistability, but not just an auxiliary predictor.

3.5.3 Originality and Value addition of the current study:

Unlike in the past reports, the novelty of this manuscript is in the following incorporated contributions:

An integrated socio-mathematics that integrates at the same time.

(a) game-theoretic payoffs,

(b) diffusion of perception through the network, and

(c) nonlinear dynamical equilibria.

Endogenous modelling of trust and risk perception, which makes them dynamic and system-shaping variables, rather than a set of assumptions. Estimable behavioural parameters that are empirically estimated with an abstract theoretical model and predictions relevant to policy. Categorical definition of behavioural tipping points, which supplies early-warning data into the design of public-health interventions. Policy-relevant interpretability, where a direct translation of model parameters can be used to create actionable strategies (trust stabilisation, network-targeted communication, and payoff restructuring).

Therefore, earlier research has looked at individual elements of the behaviour of vaccination, but the current research goes a step further to show that strategic incentives, social networks, and nonlinear dynamics work together to produce collective vaccination. This is an integrative viewpoint that is a substantive methodological and conceptual innovation in comparison to current behavioural-epidemiological models.

4. Conclusion

The idea that the process of taking a vaccine is itself a kind of social calculus, a non-biomedical choice, is not only theoretical in nature but also already supported by findings [13]. Quantitative modelling research indicates that a 5-10 per cent drop in vaccine coverage can cause a population to move off a stable herd-immunity point to become susceptible to outbreaks, especially of highly transmissible diseases ($R_0 > 3$). The further results provided in behaviour-epidemic coupled models are that small changes in perceived risk or exposure to misinformation can have a nonlinear reducing effect on coverage when trust levels drop below critical values. Empirical network studies of the COVID-19 period found that information diffusion across groups was suppressed in clustered opinion structures by over 30 per cent, which greatly increased polarisation influences on vaccine uptake. This evidence proves that strategic interdependence, network reinforcement, and tipping-point processes are the more appropriate factors ruling vaccination behaviour, in contrast to individual risk assessment [13,15].

Commented [Ma2]:

What is new about this research is that it incorporates the game-theoretic payoff structure, network contagion and dynamical systems equilibria within a single socio-mathematical framework to model collective vaccination behaviour. The model has conceptualised hesitancy as an outcome of organised social interaction instead of perceiving it as a psychological quality or demographic correlate. This interdisciplinary synthesis builds upon extant literature by providing predictive leverage: it allows one to determine key levels of trust, strategic equilibria of free-riding, and network nodes that have structural effects to trigger large-scale behavioural breakdowns before such breakdowns happen at scale [11].

Future studies ought to involve the integration of real-time digital trace information and adaptive behaviour aspects in order to enhance predictive precision. Ex post interventions Simulations based on epidemiological surveillance systems with agent interactions, may enable the policymaker to experiment with the interventions. Also, the introduction of variables of socioeconomic inequality into the payoff matrix would make a heterogeneous population more explanatory [14].

The recommendations derive directly from the modelling logic:

- ***Incentive Design Strategic***: Reduce free-riding equilibria by manipulating perceived payoffs using policy instruments (e.g., conditional access policies, social recognition incentives).
- ***Network-Based Communication***: Identify the most central or bridging actors on social networks to stimulate pro-vaccination norm cascades.
- ***Trust Stabilisation Mechanisms:*** Trust buffers through open governance and

speedy misinformation responses to avoid threshold collapse.

➢ ***Threshold Monitoring Systems***: The use of behavioural surveillance indicators to provide early warning of tipping points.

Finally, this socio-mathematical point of view is analytically accurate as well as policy relevant. It makes the shift toward systemic management of collective behaviour, as opposed to the persuasion-based approaches to public health, which highlights that lasting vaccine coverage is not achieved through information only, but through structurally informed interventions, which redefine the calculus of sociality itself [14,15].

7. Institutional Review Board (IRB) Statement

This research does not include any human subjects, human biological specimens, animal research or experimental study. The study is founded upon theoretical modelling and socio-mathematical simulation on the basis of secondary conceptual frameworks. Thus, the approval of the IRB was not necessary according to the institutional and national requirements of research ethics.

8. Patient Consent for Publication

Not applicable. The research does not engage patients, clinical information, or recognisable human subjects.

9. Clinical Trial Registry Number

Not applicable. The study is not a clinical trial or interventional study that has to be registered as a trial.

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11. Conflict of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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