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How to Effectively Promote Vaccination during Public Health Emergencies: Through Inter-Organizational Interaction

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Abstract: Vaccination is the key to interrupting the transmission of viruses, reducing public health losses, and improving the efficiency of public health emergency management. The implementation of vaccination requires communication between the government and the public, and the participation of multiple subjects. Strengthening the coordination of multiple subjects in the process of vaccination can improve the vaccination rate and broaden its scope. Therefore, from the perspective of inter-organizational interaction, a public health emergency vaccination game model based on health management departments, vaccinologists, and the public was constructed in this study. With the objective of improving the effectiveness of vaccination, the influential factors in a public health emergency vaccination game system and game subjects' strategy selection were explored using a numerical simulation analysis. The research results showed that the range of vaccination, the diversification of vaccination information release, the level of emergency coordination between health management departments and vaccinologists, and the public's awareness of emergency protection can all effectively promote vaccination. Among them, the effects of vaccination range (δ) and the diversification of vaccination information release (φ) on game subjects' strategy selection fluctuated, but did not affect the overall trend. Both the level of emergency collaboration (θ) and public safety awareness (ε) can enhance the initiative of game subjects to participate in vaccination. When the stable strategy combination formed by the game system are positive promotion strategy, active guidance strategy and active vaccination strategy, the convergence rate of health management departments and vaccinologists to form a stable strategy is greater than that of the public. Further, the implications of promoting the effective implementation of vaccination are put forward via improving the vaccination strategy, strengthening vaccination collaboration, mobilizing the enthusiasm of vaccinologists, and enhancing the initiative of the public.

Keywords: vaccination; public health emergency; evolutionary game theory; inter-organizational interaction; game system

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1. Introduction

Public health emergencies refer to major infectious disease outbreaks that harm public health [1]. They are characterized by the diversity of causes, the severity of impact, the widespread nature, the uncertainty of development, and the complexity of harm [2,3]. Moreover, the new emergency management problems triggered by the coupling of public health emergencies and other risks have gradually intensified [4,5]. Public health emergencies can cause serious losses to public health and social development. Public health emergencies such as H1N1 and COVID-19 showed that vaccination played a key role in supporting their prevention and control and improving the efficiency of emergency responses [6–8]. Initially, the public has no immunity to a new virus. Vaccination can effectively reduce the risk of morbidity, severe illness, and death [9]. Through an orderly vaccination process, an immune buffer can be established in the population to block the spread of the virus. This can help restore normal social development and residents' daily lives [10,11].

In response to COVID-19 pandemic, the Chinese government quickly invested in vaccine research and production [12]. Based on the emergency situation and virus mutation, the vaccination strategy for COVID-19 was scientifically formulated and continuously improved, including basic vaccination, first-dose vaccination, second-dose vaccination, and bridging the gap in immunization levels [13]. Existing research has explored multiple approaches to vaccine research, safeguards for vaccine supply, supervision measures for vaccine safety, and differentiated strategies for vaccination at different stages of an emergency [14].

In addition, the Chinese government drafted and issued the *Technical Vaccination Recommendations for COVID-19 Vaccines in China* to help health departments and disease control agencies at all levels to guide units to carry out COVID-19 vaccination. During this period, the Chinese government and health management departments also actively guided key groups to take the initiative to be vaccinated, and increased the coverage rate of vaccination. Local governments also implemented vaccination programs according to local conditions and based on regional characteristics and virus transmission characteristics. Strategies included developing online reservation vaccination procedures and establishing fixed and temporary vaccination sites to complement each other. Some scholars have summarized active vaccination measures by integrating the government's experience in coping with public health emergencies and focusing on research topics such as regional differences, innovative models, and emerging media [15–17].

Due to the uncertainty involved in public health emergencies, the mutation of the virus and its ability to evade immunity [18], vaccines are not always suitable and so vaccination may not be carried out only once [19,20]. Strategies for vaccination at different stages are developed to match the life cycle characteristics of public health emergencies and emergency needs [21]. For example, the Chinese government deployed a "three-step" strategy based on the production of vaccines and the judgment of risk factors in responding to COVID-19. They carried out successive vaccination steps for both high-risk and general groups. The relevant studies considered vaccination as part of overall research on the prevention and control of public health emergencies. After discussing the dynamic characteristics and differences of the emergency management, deployment strategies and the focus of governments on vaccines in different emergency stages are summarized [22,23].

The practice of public health emergency vaccination shows that vaccination programs involve the participation and coordination of multiple subjects. Among them, the government and relevant departments are the organizers of vaccination, coordinating the production, supply, and delivery of vaccines [24]. The public is the main subject participating in vaccination, and the coverage rate, number of people vaccinated, and proportion of the population vaccinated are important factors affecting the effectiveness of a vaccination program [25]. Scientists are important for engaging in communication with the public and disseminating scientific and technological knowledge. As a group of scientists, vaccinologists play an important role in assisting the government in promoting vaccination. As well as introducing the benefits of vaccination to the public, they can clarify matters needing attention and publicize a vaccination policy [26]. How to stimulate the initiative of multiple subjects involved in vaccination and improve the overall efficiency of vaccination has significance for blocking the spread of viruses, improving the efficiency of public health emergency responses, and reducing losses of social development [27]. The issue of inter-organizational interaction in vaccination has not been addressed in existing studies. There are few research results on how to promote vaccination and improve the efficiency of vaccination from the perspective of inter-organizational interaction.

Therefore, the research objective of this study is to clarify the relationships between the multiple subjects involved in vaccination, and to condense the inter-organizational interaction mechanism that can promote the implementation of vaccination. Evolutionary game theory (EGT) is the research method to analyze the relationships between subjects and the characteristics of strategies, which puts both subjects and strategies into the game system [28–30]. Moreover, EGT can clearly describe the dynamic evolution of a subject's strategy, analyze the path to determine the subject's strategy optimization, and provide observation schemes for clarifying the strategy combination needed to promote public health emergency vaccination.

At present, existing studies have applied EGT to the study of public health emergencies from the perspective of inter-organizational relationships. The studies focus on the establishment of public health emergency collaboration systems [31–33], improving the efficiency of emergency and medical resource allocation [34,35], improving the early warning mechanisms of public health emergencies [36], taking psychological intervention measures for public health emergencies [37], and improving information release strategies during public health emergencies. In addition to government and health management departments, communities, the public, social organizations, volunteers, pharmaceutical enterprises, hospitals, whistle-blowers, and media organizations are also considered as game subjects involved in public health emergencies and influencing decision making about emergency management [23,38]. Furthermore, existing studies pay particular attention to research topics such as enriching the public's participation methods, enhancing the public's risk awareness, and implementing the public's protection measures. Some scholars have added factors such as reward and punishment measures [39], information disclosure [40], and psychological intervention [37] into the relationships between the government and the public to further explain the dynamic evolution and influencing mechanism of communication strategies between the government and the public. It can be seen that EGT can provide methodological support for analyzing the communication and interaction between the government and the public.

To sum up, based on the types of subjects participating in public health emergency vaccination and the relationships between subjects, this study will construct a public health emergency vaccination game model based on health management departments, vaccinologists, and the public by combining practices associated with responding to COVID-19 and promoting vaccination in China. At the same time, based on the evolutionary stability of the game system and the game subject's strategy selection, the influencing factors of the public health emergency vaccination game system will be discussed. Then, the decision-making scheme and realization path to promote the effective implementation of vaccination can be explored. The research results will provide a scientific reference to improve the effectiveness of vaccination and ease public health emergencies.

The structure of this study is as follows: Section 2 describes the research questions and research design. Model settings are proposed based on vaccination practice, and a public health emergency vaccination game model is derived based on the payoff matrix of game subjects. Section 3 introduces a numerical simulation analysis. The influence of the range of vaccination, the diversification of vaccination information release, the level of emergency collaboration between health management departments and vaccinologists, and the public's awareness of emergency protection in the public health emergency vaccination game system are discussed. Section 4 further discusses how to effectively promote vaccination based on the results of a simulation analysis. In addition, the contribution, limitations, and future research direction of this study are put forward. Section 5 summarizes the conclusions and discusses the implications of improving the efficiency of vaccination in terms of improving the vaccination strategy, strengthening collaborations, mobilizing vaccinologists' enthusiasm, and enhancing the public's initiative.

2. Research Framework and Game Model

2.1. Description of Research Problems and Research Design

Vaccination is an important method to deal with public health emergencies and viral epidemics. The implementation of vaccination can reduce the intensity of virus transmission, establish an immune buffer, block the spread of epidemics, and prevent public health emergencies.

In the prevention and control of public health emergencies, the government and relevant departments, immunologists, vaccinologists, and the public are the main subjects influencing the implementation of vaccination. How to promote the orderly cooperation of different subjects in vaccination and strengthen the efficiency of vaccination are important research issues for strengthening the response to public health emergencies. Therefore, this study will address how to improve vaccination rates through collaboration between health management departments, vaccinologists, and the public. First, health management departments need to cover the costs of researching vaccines, organizing vaccination, and responding to vaccination problems to ensure effective implementation. Second, vaccinologists must encourage the public to participate in vaccination through publicity involving authoritative information and dealing with any problems. Vaccinologists can enhance the public's understanding of vaccines, eliminate worries and confusion about vaccination, and reduce and supplement the emergency costs paid by health management departments to a certain extent. Third, the public can choose to participate in vaccination in a timely and reasonable manner based on their existing awareness and guidance about vaccination publicity matters [41], which can effectively improve vaccination coverage. As health management departments, vaccinologists, and the public become more engaged and proactive, public health emergency vaccination can become more effective.

To this end, this study will identify the interactions and game relationships between health management departments, vaccinologists, and the public, and construct a public health emergency vaccination game system. Considering the benefits of game subjects in different game situations, a payoff matrix can be constructed, and an evolutionary game model will be derived by calculation. The results can provide a theoretical basis on how to effectively promote vaccination from the perspective of inter-organizational interaction.

2.2. Settings and Explanation of Public Health Emergency Vaccination Game Model

This study constructs a public health emergency vaccination game model for vaccination scenarios in public health emergencies, which consists of health management departments, vaccinologists, and the public. The game relationships among game subjects and the general situation of a public health emergency vaccination game system are shown in Figure 1. The relevant settings of a public health emergency vaccination game model are put forward.

Setting 1: In the public health emergency vaccination game system, health management departments, vaccinologists, and the public are all characterized by bounded rationality. Due to the complexity and uncertainty of public health emergency vaccination, there is information asymmetry between game subjects. When game subjects participate in public health emergency vaccination, the strategies of health management departments, vaccinologists, and the public are random and independent.

As a component of the government, health management departments are responsible for dealing with public health emergencies, and also undertake emergency tasks such as vaccine research, vaccination, and information release. Health management departments can select a positive vaccination promotion strategy to cope with public health emergencies, curb viral epidemics, and reduce the losses of social development. Moreover, due to the participation of vaccinologists in vaccination, the protection awareness of the public, and/or the high costs of promotion vaccination, health management departments may select a negative promotion strategy. Based on this, the probabilities of selecting a positive promotion strategy or a negative promotion strategy are x and $1 - x$, where $x \in [0, 1]$.

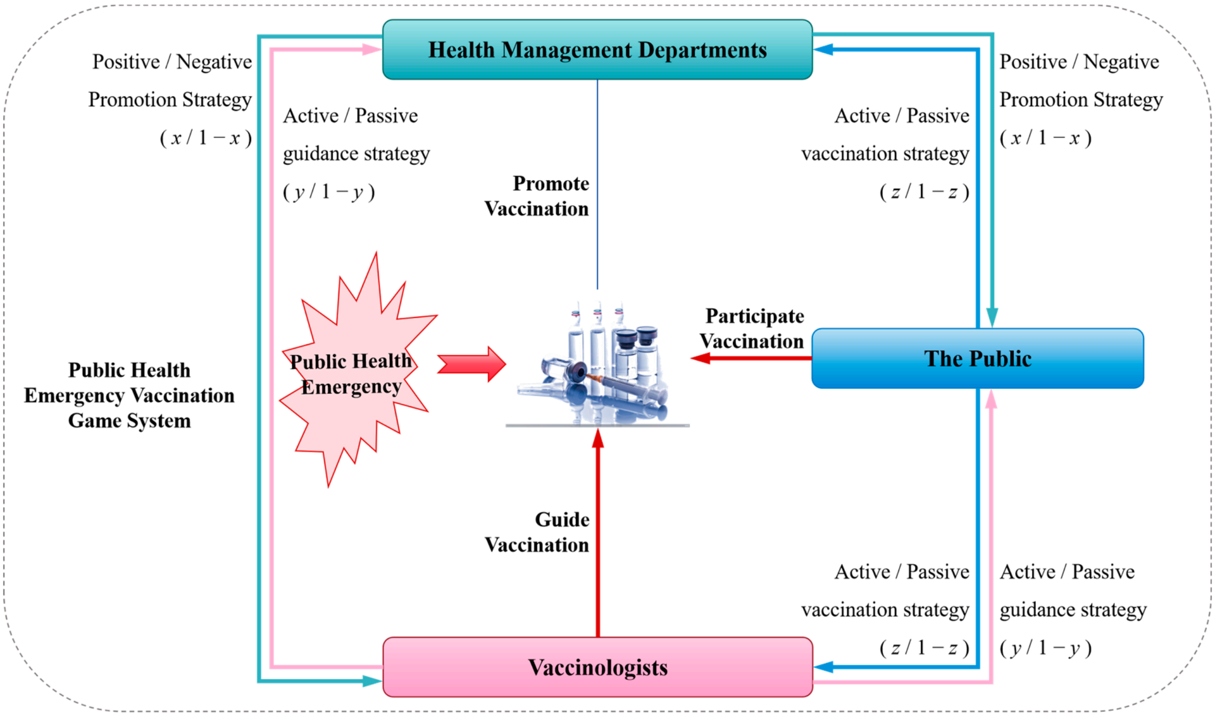


Figure 1. Graphical representation of the public health emergency vaccination game system.

Vaccinologists can provide answers to the public about the effectiveness, applicability, contraindications, and side effects of vaccines, which is an important mode of support for health management departments when promoting vaccination. Based on vaccinologists' initiatives for promoting participation in vaccination, they can select an active vaccination strategy or a passive vaccination strategy. The corresponding probabilities of strategy selection are y and $1 - y$, where $y \in [0, 1]$.

When dealing with public health emergencies, the public will select different game strategies due to differences in their understanding of viruses and vaccines, as well as their protection capabilities. However, with the promotion of health management departments and the guidance of vaccinologists, the public's strategy selection will change. Specifically, the probabilities of the public selecting an active vaccination strategy or a passive vaccination strategy are z and $1 - z$, where $z \in [0, 1]$.

Setting 2: Health management departments pay various costs for promoting vaccination. C_1 are the costs of technological innovation and clinical trials paid by health management departments in developing vaccines suitable for public health emergencies involving viruses. C_2 are the costs of resource consumption, organization management, and human resources paid by health management departments to formulate vaccination strategies, manage vaccine information, and ensure vaccination implementation. C_3 are the costs of resource consumption, organization management, and human resources paid by health management departments to respond to the public about vaccination issues and to implement vaccination publicity. K are the information and communication costs paid by vaccinologists to guide the public to participate in vaccination, inform people about the use and applicability of vaccines, and dispel unhelpful rumors about vaccination. W represents the time and manpower costs of the public participation in vaccination, as facilitated by health management departments and guided by vaccinologists.

Setting 3: L_1, L_2, and L_3 are the perceived losses of health management departments, vaccinologists, and the public, respectively, caused by public health emergencies. Among them, L_1 refers to the losses caused by public health emergencies to social and economic development, as well as human casualties. L_2 and L_3 refer to the economic losses and personal safety losses caused by public health emergencies to vaccinologists and the public, respectively. E_1, E_2, and E_3 are the perceived benefits to health management departments, vaccinologists, and the public, respectively. Among them, E_1 refers to health management departments' perceived benefits of the social security and economic development gained by promoting vaccination.

E_2 refers to the perceived benefits of security and protection obtained by vaccinologists who guide the public to participate in vaccination. E_3 refers to the public's perceived benefits of vaccination for their own health and safety. G_1 refers to the public credibility benefits gained by health management departments when they formulate vaccination programs and promote vaccination to curb virus epidemics, prevent and control public health emergencies, and mitigate losses. G_2 refers to the authority and reputation benefits gained by vaccinologists by guiding the public to participate in vaccination and improving the public's protection ability.

Setting 4: α is the implementation intensity required of health management departments to promote vaccination. The larger α is, the higher the costs paid by health management departments. Moreover, the effectiveness of vaccination is greater, as is the credibility of the benefits obtained. When health management departments select the positive promotion strategy, $\alpha = 1$. β is the initiative of vaccinologists to guide the public to participate in vaccination. The larger β is, the higher the costs vaccinologists have to pay, and the greater the reputation benefits they accrue. When vaccinologists select the active guidance strategy, $\beta = 1$. γ is the public's initiative to participate in vaccination. A larger γ means that the public needs to pay more to participate in vaccination organized by health management departments. When the public selects the active vaccination strategy, $\gamma = 1$.

Setting 5: The range of vaccination (δ) indicates the area and number of people to be vaccinated in response to a public health emergency. A high level of δ indicates a wide range of vaccination, multiple vaccination methods, and a high vaccination rate. Correspondingly, health management departments, vaccinologists, and the public have a lower perception of the losses involved in public health emergencies. It can be seen that the range of vaccination (δ) is directly proportional to the implementation costs of health management departments, and inversely proportional to the perceived losses of game subjects. In addition, the range of vaccination (δ) will be driven by the health management departments' implementation of vaccination (intensity = α), vaccinologists' initiatives to participate in vaccination (β), and the public's initiative to vaccinate (γ).

The diversification of vaccination information release (φ) is a parameter describing the information release channels or methods by which health management departments and vaccinologists guide the public to participate in vaccination. A larger φ indicates more information exchange methods by health management departments and vaccinologists and more channels for the public to receive vaccination information. The diversification of vaccination information release (φ) is proportional to the costs (C_3) for health management departments to respond to the public and the costs (K) for vaccinologists to present vaccine-related information. Moreover, the higher the diversification of vaccination information release, the higher the public credibility benefits (G_1) of health management departments, and the higher the reputation benefits (G_2) of vaccinologists.

The level of emergency collaboration between health management departments and vaccinologists (θ) describes the communication efficiency between health management departments and the guiding effectiveness of vaccination. The greater θ is, the better the level of information exchange between health management departments and vaccinologists on vaccine research, allocation, and distribution. When health management departments select a positive promotion strategy and vaccinologists select an active guidance strategy, θ is inversely proportional to the costs (C_3) for health management departments to respond to the public and the costs (K) for vaccinologists to present vaccine-related information. At this point, the higher the level of emergency collaboration, the lower the costs of the implementation of vaccination by health management departments and vaccinologists.

ε is the public's awareness of emergency protection. The larger ε is, the greater the public's ability to acquire information about public health emergencies and virus prevention, so as to better protect their health. The public's awareness of emergency protection can be cultivated in non-emergency periods and learned during emergency periods. In this study, the public's awareness of emergency protection was seen to affect the public's willingness to vaccinate and their belief in the effectiveness of vaccination. Specifically, the public's awareness of emergency protection is directly proportional to the perceived benefits vaccination has for health management departments, vaccinologists, and the public.

Based on the above settings, the corresponding parameters of the game subjects in the game model can be obtained (Figure 2). The range and meaning of the parameters involved in the public health emergency vaccination game system are presented in Table 1.

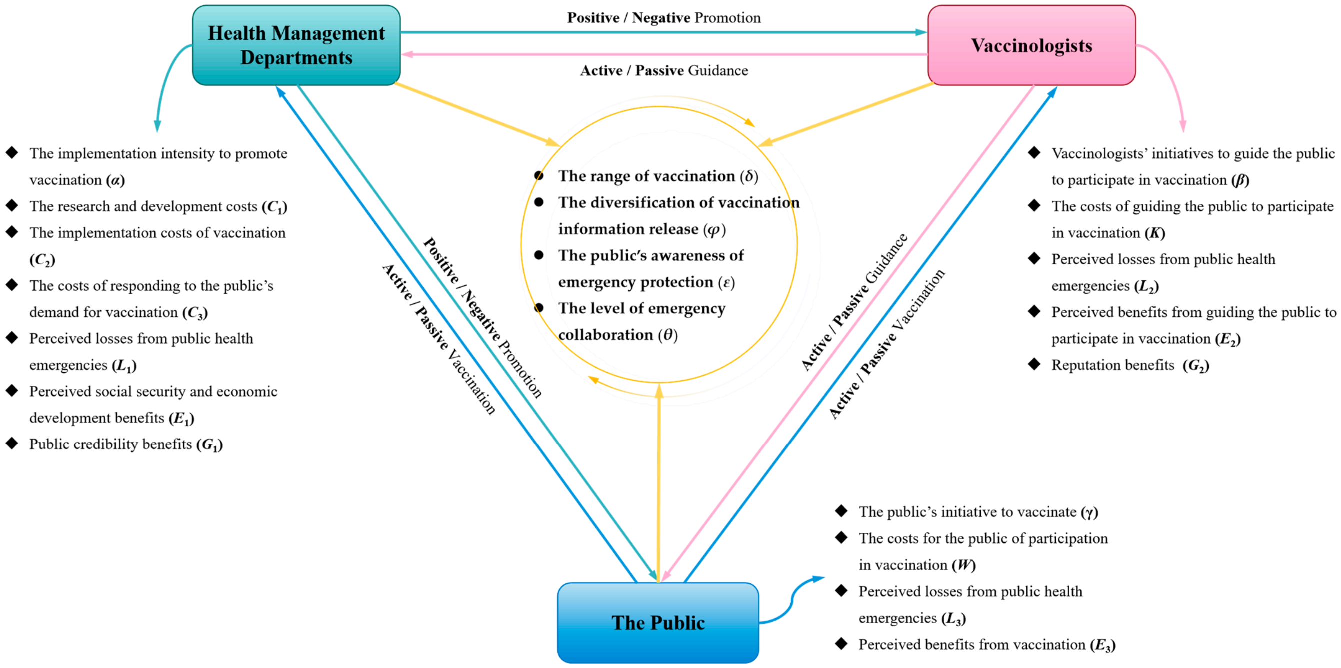


Figure 2. Correspondence between parameters and game subjects.

Table 1. Range and meaning of parameters in the public health emergency vaccination game system.

Parameter	Meaning of Parameter	Range of Parameter
C_1	The research and development costs of vaccines for health management departments.	$C_1 \in (0, +\infty)$
C_2	The implementation costs of vaccination for health management departments.	$C_2 \in (0, +\infty)$
C_3	The costs for health management departments of responding to the public's demand for vaccination.	$C_3 \in (0, +\infty)$
K	The costs for vaccinologists of guiding the public to participate in vaccination.	$K \in (0, +\infty)$
W	The costs for the public of participation in vaccination.	$W \in (0, +\infty)$
L_1	Health management departments' perceived losses from public health emergencies.	$L_1 \in (0, +\infty)$
L_2	Vaccinologists' perceived losses from public health emergencies.	$L_2 \in (0, +\infty)$
L_3	The public's perceived losses from public health emergencies.	$L_3 \in (0, +\infty)$
E_1	Health management departments' perceived social security and economic development benefits from promoting vaccination.	$E_1 \in (0, +\infty)$
E_2	Vaccinologists' perceived benefits from guiding the public to participate in vaccination.	$E_2 \in (0, +\infty)$

Table 1. *Cont.*

Parameter	Meaning of Parameter	Range of Parameter
E_3	The public's perceived benefits from vaccination.	$E_3 \in (0, +\infty)$
G_1	Public credibility benefits gained by health management departments for promoting vaccination and effectively preventing and controlling public health emergencies.	$G_1 \in (0, +\infty)$
G_2	Reputation benefits gained by vaccinologists for guiding the public to participate in vaccination.	$G_2 \in (0, +\infty)$
α	The implementation intensity of health management departments to promote vaccination.	$\alpha \in [0, 1]$
β	Vaccinologists' initiatives to guide the public to participate in vaccination.	$\beta \in [0, 1]$
γ	The public's initiative to vaccinate.	$\gamma \in [0, 1]$
δ	The range of vaccination.	$\delta \in [0, 1]$
φ	The diversification of vaccination information release.	$\varphi \in [0, 1]$
θ	The level of emergency collaboration between health management departments and vaccinologists.	$\theta \in [0, 1]$
ε	The public's awareness of emergency protection when facing public health emergencies.	$\varepsilon \in [0, 1]$

2.3. Derivation of Public Health Emergency Vaccination Game Model

Based on the game relationships between health management departments, vaccinologists, and the public, and considering the payoff and benefits of game subjects in different game scenarios, a payoff matrix of the public health emergency vaccination game model is sorted out. Table 2 shows a total of eight game strategy combinations corresponding to the public health emergency vaccination game system.

Table 2. Payoff matrix of the public health emergency vaccination game model.

Health Management Departments	Vaccinologists	The Public: Active Vaccination Strategy z	The Public: Passive Vaccination Strategy $1-z$
Positive promotion strategy x	Active guidance strategy y	$-C_1-\delta C_2-\varphi(1-\theta)C_3-(1-\delta)L_1+\varepsilon E_1+\varphi G_1$, $-\varphi(1-\theta)K-(1-\delta)L_2+\varepsilon E_2+\varphi G_2$, $-W-(1-\delta)L_3+\varepsilon E_3$	$-C_1-\delta C_2-\varphi(1-\theta)C_3-(1-\gamma\delta)L_1+\gamma\varepsilon E_1+\varphi G_1$, $-\varphi(1-\theta)K-(1-\gamma\delta)L_2+\gamma\varepsilon E_2+\varphi G_2$, $-\gamma W-(1-\gamma\delta)L_3+\gamma\varepsilon E_3$
	Passive guidance strategy $1-y$	$-C_1-\delta C_2-\varphi C_3-(1-\beta\delta)L_1+\varepsilon E_1+\beta\varphi G_1$, $-\beta\varphi K-(1-\beta\delta)L_2+\varepsilon E_2$, $-W-(1-\beta\delta)L_3+\varepsilon E_3$	$-C_1-\delta C_2-\varphi C_3-(1-\beta\gamma\delta)L_1+\gamma\varepsilon E_1+\beta\varphi G_1$, $-\beta\varphi K-(1-\alpha\beta\delta)L_2+\varepsilon E_2$, $-\gamma W-(1-\beta\gamma\delta)L_3+\gamma\varepsilon E_3$
Negative promotion strategy $1-x$	Active guidance strategy Y	$-\alpha C_1-\alpha\delta C_2-\alpha\varphi C_3-(1-\alpha\delta)L_1+\varepsilon E_1$, $-\varphi K-(1-\alpha\delta)L_2+\varepsilon E_2+\alpha\varphi G_2$, $-W-(1-\alpha\delta)L_3+\varepsilon E_3$	$-\alpha C_1-\alpha\delta C_2-\alpha\varphi C_3-(1-\alpha\gamma\delta)L_1+\gamma\varepsilon E_1$, $-\varphi K-(1-\alpha\gamma\delta)L_2+\gamma\varepsilon E_2+\alpha\varphi G_2$, $-\gamma W-(1-\alpha\gamma\delta)L_3+\gamma\varepsilon E_3$
	Passive guidance strategy $1-y$	$-\alpha C_1-\alpha\delta C_2-\alpha\varphi C_3-(1-\alpha\beta\delta)L_1+\varepsilon E_1$, $-\beta\varphi K-(1-\beta\gamma\delta)L_2+\gamma\varepsilon E_2$, $-W-(1-\alpha\beta\delta)L_3+\varepsilon E_3$	$-\alpha C_1-\alpha\delta C_2-\alpha\varphi C_3-(1-\alpha\beta\gamma\delta)L_1+\gamma\varepsilon E_1$, $-\beta\varphi K-(1-\alpha\beta\gamma\delta)L_2+\gamma\varepsilon E_2$, $-\gamma W-(1-\alpha\beta\gamma\delta)L_3+\gamma\varepsilon E_3$

2.3.1. Replication Dynamic Equation (RDE) of Health Management Departments

According to the payoff matrix of the public health emergency vaccination game system, the prospective benefits of health management departments selecting a positive promotion strategy, U_{x1}, are as follows:

$$\begin{array}{l} U_{x1}=yz[-C_1-\delta C_2-\varphi(1-\theta)C_3-(1-\delta)L_1+\varepsilon E_1+\varphi G_1]+y(1-z)[-C_1-\delta C_2-\varphi(1-\theta)C_3-(1-\gamma\delta)L_1+\gamma\varepsilon E_1+\varphi G_1] \\ +z(1-y)[-C_1-\delta C_2-\varphi C_3-(1-\beta\delta)L_1+\varepsilon E_1+\beta\varphi G_1]+(1-y)(1-z)[-C_1-\delta C_2-\varphi C_3-(1-\beta\gamma\delta)L_1+\gamma\varepsilon E_1+\beta\varphi G_1] \end{array}. \quad (1)$$

If health management departments select a negative promotion strategy, the prospective benefits, U_{x2}, are as follows:

$$\begin{aligned} U_{x2} = & yz[-\alpha C_1 - \alpha\delta C_2 - \alpha\varphi C_3 - (1-\alpha\delta)L_1 + \varepsilon E_1] + y(1-z)[-\alpha C_1 - \alpha\delta C_2 - \alpha\varphi C_3 - (1-\alpha\gamma\delta)L_1 + \gamma\varepsilon E_1] \\ & + z(1-y)[-\alpha C_1 - \alpha\delta C_2 - \alpha\varphi C_3 - (1-\alpha\beta\delta)L_1 + \varepsilon E_1] + (1-y)(1-z)[-\alpha C_1 - \alpha\delta C_2 - \alpha\varphi C_3 - (1-\alpha\beta\gamma\delta)L_1 + \gamma\varepsilon E_1] \end{aligned} . \quad (2)$$

The RDE of health management departments' promotion vaccination strategy is as follows:

$$P(x) = \frac{dx}{dt} = x(1-x)[-(1-\alpha)(C_1 + \delta C_2 + \varphi C_3) + y\theta\varphi C_3 + (1-\alpha)(y - y\beta + \beta)(z - z\gamma + \gamma)\delta L_1 + (y - y\beta + \beta)\varphi G_1]. \quad (3)$$

2.3.2. RDE of Vaccinologists

In the vaccination game system, the prospective benefits of vaccinologists selecting the active guidance strategy, U_{y1}, are as follows:

$$\begin{aligned} U_{y1} = & xz[-\varphi(1-\theta)K - (1-\delta)L_2 + \varepsilon E_2 + \varphi G_2] + z(1-x)[-\varphi K - (1-\alpha\delta)L_2 + \varepsilon E_2 + \alpha\varphi G_2] \\ & + x(1-z)[-\varphi(1-\theta)K - (1-\gamma\delta)L_2 + \gamma\varepsilon E_2 + \varphi G_2] + (1-x)(1-z)[-\varphi K - (1-\alpha\gamma\delta)L_2 + \gamma\varepsilon E_2 + \alpha\varphi G_2] \end{aligned} . \quad (4)$$

If vaccinologists select a passive guidance strategy, the prospective benefits, U_{y2}, are as follows:

$$\begin{aligned} U_{y2} = & xz[-\beta\varphi K - (1-\beta\delta)L_2 + \varepsilon E_2] + z(1-x)[-\beta\varphi K - (1-\alpha\beta\delta)L_2 + \varepsilon E_2] \\ & + x(1-z)[-\beta\varphi K - (1-\beta\gamma\delta)L_2 + \gamma\varepsilon E_2] + (1-x)(1-z)[-\beta\varphi K - (1-\alpha\beta\gamma\delta)L_2 + \gamma\varepsilon E_2] \end{aligned} . \quad (5)$$

Further, the RDE of vaccinologists' guiding vaccination strategy is as follows:

$$Q(y) = \frac{dy}{dt} = y(1-y)[-(1-\beta)\varphi K + x\theta\varphi K + (1-\beta)(x - x\alpha + \alpha)(z - z\gamma + \gamma)\delta L_2 + (x - x\alpha + \alpha)\varphi G_2]. \quad (6)$$

2.3.3. RDE of the Public

In the vaccination game system, the prospective benefits of the public selecting the active vaccination strategy, U_{z1}, are as follows:

$$\begin{aligned} U_{z1} = & xy[-W - (1-\delta)L_3 + \varepsilon E_3] + x(1-y)[-W - (1-\beta\delta)L_3 + \varepsilon E_3] + \\ & y(1-x)[-W - (1-\alpha\delta)L_3 + \varepsilon E_3] + (1-x)(1-y)[-W - (1-\alpha\beta\delta)L_3 + \varepsilon E_3] \end{aligned} . \quad (7)$$

The prospective benefits of the public under a passive vaccination strategy, U_{z2}, are as follows:

$$\begin{aligned} U_{z2} = & xy[-\gamma W - (1-\gamma\delta)L_3 + \gamma\varepsilon E_3] + x(1-y)[-\gamma W - (1-\beta\gamma\delta)L_3 + \gamma\varepsilon E_3] + \\ & y(1-x)[-\gamma W - (1-\alpha\gamma\delta)L_3 + \gamma\varepsilon E_3] + (1-x)(1-y)[-\gamma W - (1-\alpha\beta\gamma\delta)L_3 + \gamma\varepsilon E_3] \end{aligned} . \quad (8)$$

Further, the RDE of the public's vaccination strategy is as follows:

$$R(z) = \frac{dz}{dt} = z(1-z)[-(1-\gamma)(W - \varepsilon E_3) + (1-\gamma)(x - x\alpha + \alpha)(y - y\beta + \beta)\delta L_3]. \quad (9)$$

Based on the RDE of health management departments, vaccinologists, and the public, a public health emergency vaccination game model is obtained, as shown in Equation (10):

$$\begin{cases} P(x) = x(1-x)[-(1-\alpha)(C_1 + \delta C_2 + \varphi C_3) + y\theta\varphi C_3 + (1-\alpha)(y - y\beta + \beta)(z - z\gamma + \gamma)\delta L_1 + (y - y\beta + \beta)\varphi G_1] \\ Q(y) = y(1-y)[-(1-\beta)\varphi K + x\theta\varphi K + (1-\beta)(x - x\alpha + \alpha)(z - z\gamma + \gamma)\delta L_2 + (x - x\alpha + \alpha)\varphi G_2] \\ R(z) = z(1-z)[-(1-\gamma)(W - \varepsilon E_3) + (1-\gamma)(x - x\alpha + \alpha)(y - y\beta + \beta)\delta L_3] \end{cases} . \quad (10)$$

2.4. Stability Analysis of Public Health Emergency Vaccination Game Model

2.4.1. Equilibrium Points of Public Health Emergency Vaccination Game Model

Combined with the RDE of health management departments, vaccinologists and the public, the replicated dynamic system for the public health emergency vaccination game can be obtained. On this basis, the Jacobi matrix of the replicated dynamic system J is given as:

$$J = \begin{pmatrix} \frac{\partial P(x)}{\partial x} & \frac{\partial P(x)}{\partial y} & \frac{\partial P(x)}{\partial z} \\ \frac{\partial Q(y)}{\partial x} & \frac{\partial Q(y)}{\partial y} & \frac{\partial Q(y)}{\partial z} \\ \frac{\partial R(z)}{\partial x} & \frac{\partial R(z)}{\partial y} & \frac{\partial R(z)}{\partial z} \end{pmatrix}. \tag{11}$$

The Jacobi matrix is used to analyze the local asymptotic stability of equilibrium points in the system. The eight pure policy equilibrium points of the system can be obtained as E_1 (0,0,0), E_2 (0,1,0), E_3 (0,0,1), E_4 (1,0,0), E_5 (1,1,0), E_6 (1,0,1), E_7 (0,1,1), and E_8 (1,1,1). At the same time, the elements of matrix J are brought in to obtain the eigenvalues of each equilibrium point of the system, as shown in Table 3.

Table 3. Equilibrium points and eigenvalues of the replicated dynamic system.

Equilibrium Point	Eigenvalue		
	λ_1	λ_2	λ_3
E_1 (0,0,0)	$-(1-\alpha)(C_1+\delta C_2+\varphi C_3)+(1-\alpha)\beta\gamma\delta L_1+\beta\varphi G_1$	$-(1-\beta)\varphi K+(1-\beta)\alpha\gamma\delta L_2+\alpha\varphi G_2$	$-(1-\gamma)(W-\varepsilon E_3)+(1-\gamma)\alpha\beta\delta L_3$
E_2 (0,1,0)	$-(1-\alpha)(C_1+\delta C_2+\varphi C_3)+\theta\varphi C_3+(1-\alpha)\gamma\delta L_1+\varphi G_1$	$(1-\beta)\varphi K-(1-\beta)\alpha\gamma\delta L_2-\alpha\varphi G_2$	$-(1-\gamma)(W-\varepsilon E_3)+(1-\gamma)\alpha\delta L_3$
E_3 (0,0,1)	$-(1-\alpha)(C_1+\delta C_2+\varphi C_3)+(1-\alpha)\beta\delta L_1+\beta\varphi G_1$	$-(1-\beta)\varphi K+(1-\beta)\alpha\delta L_2+\alpha\varphi G_2$	$(1-\gamma)(W-\varepsilon E_3)-(1-\gamma)\alpha\beta\delta L_3$
E_4 (1,0,0)	$(1-\alpha)(C_1+\delta C_2+\varphi C_3)-(1-\alpha)\beta\gamma\delta L_1-\beta\varphi G_1$	$-(1-\beta)\varphi K+\theta\varphi K+(1-\beta)\gamma\delta L_2+\varphi G_2$	$-(1-\gamma)(W-\varepsilon E_3)+(1-\gamma)\beta\delta L_3$
E_5 (1,1,0)	$(1-\alpha)(C_1+\delta C_2+\varphi C_3)-\theta\varphi C_3-(1-\alpha)\gamma\delta L_1-\varphi G_1$	$(1-\beta)\varphi K-\theta\varphi K-(1-\beta)\gamma\delta L_2-\varphi G_2$	$-(1-\gamma)(W-\varepsilon E_3)+(1-\gamma)\delta L_3$
E_6 (1,0,1)	$(1-\alpha)(C_1+\delta C_2+\varphi C_3)-(1-\alpha)\beta\delta L_1-\beta\varphi G_1$	$-(1-\beta)\varphi K+\theta\varphi K+(1-\beta)\delta L_2+\varphi G_2$	$(1-\gamma)(W-\varepsilon E_3)-(1-\gamma)\beta\delta L_3$
E_7 (0,1,1)	$-(1-\alpha)(C_1+\delta C_2+\varphi C_3)+\theta\varphi C_3+(1-\alpha)\delta L_1+\varphi G_1$	$(1-\beta)\varphi K-(1-\beta)\alpha\delta L_2-\alpha\varphi G_2$	$(1-\gamma)(W-\varepsilon E_3)-(1-\gamma)\alpha\delta L_3$
E_8 (1,1,1)	$(1-\alpha)(C_1+\delta C_2+\varphi C_3)-\theta\varphi C_3-(1-\alpha)\delta L_1-\varphi G_1$	$(1-\beta)\varphi K-\theta\varphi K-(1-\beta)\delta L_2-\varphi G_2$	$(1-\gamma)(W-\varepsilon E_3)-(1-\gamma)\delta L_3$

According to Lyapunov's stability theorem, the replicative dynamic system is asymptotically stable when the Jacobi matrix J has negative real parts. Therefore, when the eigenvalues at an equilibrium point in Table 3 satisfy all $\lambda_i < 0$ (i = 1, 2, 3), the equilibrium point is asymptotically stable. When one of the eigenvalues at the equilibrium point is >0, the equilibrium point is unstable.

2.4.2. Analysis of Strategic Stability of Health Management Departments

According to the stability theorem of RDE, the probability of health management departments' promotion vaccination strategy selection is stable when it is satisfied $P(x) = 0$ and $P'(x) < 0$. Therefore, it follows that when $y = y_0 = \frac{-(1-\alpha)(C_1+\delta C_2+\varphi C_3)+(1-\alpha)(z-z\gamma+\gamma)\beta\delta L_1+\beta\varphi G_1}{-y\theta\varphi C_3-(1-\alpha)(1-\beta)(z-z\gamma+\gamma)\delta L_1-(1-\beta)\varphi G_1}$ or $z = z_0 = \frac{-(1-\alpha)(C_1+\delta C_2+\varphi C_3)+y\theta\varphi C_3+(1-\alpha)(y-y\beta+\beta)\gamma\delta L_1+(y-y\beta+\beta)\varphi G_1}{-(1-\alpha)(1-\gamma)(y-y\beta+\beta)\delta L_1}$, there is $P(x) \equiv 0$. At this point, any promotion vaccination strategy selected by health management departments will not follow the public health emergency vaccination game system evolution changes.

Further, $P'(x) = (1-2x)[-(1-\alpha)(C_1+\delta C_2+\varphi C_3)+y\theta\varphi C_3+(1-\alpha)(y-y\beta+\beta)(z-z\gamma+\gamma)\delta L_1+(y-y\beta+\beta)\varphi G_1]$ can be obtained by taking the derivative of $P(x)$. When $y > y_0$ or $z > z_0$, there is $P'(x)|_{x=0} > 0$ and $P'(x)|_{x=1} < 0$. It can be seen that x = 1 (positive promotion strategy) is a stable strategy of health management departments. When $y < y_0$ or $z < z_0$, there is $P'(x)|_{x=0} < 0$ and $P'(x)|_{x=1} > 0$. It can be seen that x = 0 (negative promotion strategy) is a stable strategy of health management departments.

In summary, the evolutionary phase diagram of the promotion vaccination strategy of health management departments can be obtained (Figure 3). The volume of region I and region II represent the probability of health management departments to select negative promotion strategy and positive promotion strategy, respectively.

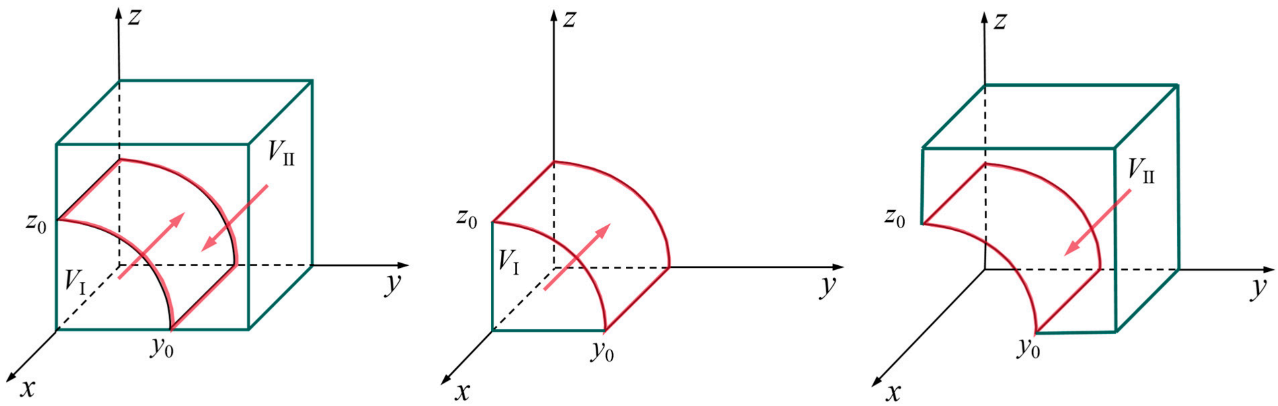


Figure 3. Evolutionary phase diagram of health management departments' strategies.

2.4.3. Analysis of Strategic Stability of Vaccinologists

When $Q(y) = 0$ and $Q'(y) < 0$ are satisfied, the probability of vaccinologists' guidance strategy selection is stable. It follows that when $x = x_0 = \frac{-(1-\beta)\varphi K+(1-\beta)(z-z\gamma+\gamma)\alpha\delta L_2+\alpha\varphi G_2}{-\theta\varphi K-(1-\beta)(1-\alpha)(z-z\gamma+\gamma)\delta L_2-(1-\alpha)\varphi G_2}$ or $z = z_0 = \frac{-(1-\beta)\varphi K+x\theta\varphi K+(1-\beta)(x-x\alpha+\alpha)\gamma\delta L_2+(x-x\alpha+\alpha)\varphi G_2}{-(1-\beta)(1-\gamma)(x-x\alpha+\alpha)\delta L_2}$, there is $Q(y) \equiv 0$. At this time, any guidance strategy selected by vaccinologists is stable and is not affected by the evolution of the game system.

Further, $Q'(y) = (1-2y)[-(1-\beta)\varphi K + x\theta\varphi K + (1-\beta)(x-x\alpha+\alpha)(z-z\gamma+\gamma)\delta L_2 + (x-x\alpha+\alpha)\varphi G_2]$ can be obtained by taking the derivative of $Q(y)$. When $x > x_0$ or $z > z_0$, there is $Q'(y)\big|_{y=0} > 0$ and $Q'(y)\big|_{y=1} < 0$. It can be seen that $y = 1$ (active guidance strategy) is a stable strategy of vaccinologists. When $x < x_0$ or $z < z_0$, there is $Q'(y)\big|_{y=0} < 0$ and $Q'(y)\big|_{y=1} > 0$. It can be seen that $y = 0$ (passive guidance strategy) is a stable strategy of vaccinologists.

In summary, the evolutionary phase diagram of the guidance strategy of vaccinologists can be obtained (Figure 4). The volume of region III and region IV represent the probability of vaccinologists selecting passive guidance strategy and active guidance strategy, respectively.

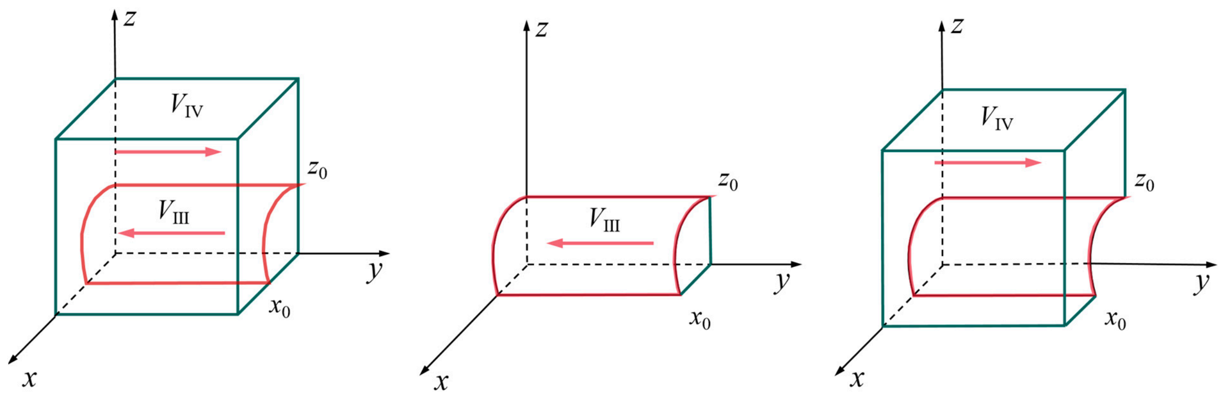


Figure 4. Evolutionary phase diagram of vaccinologists' strategies.

2.4.4. Analysis of Strategic Stability of the Public

Similarly, when $R(z) = 0$ and $R'(z) < 0$ are satisfied, the probability of the public's vaccination strategy selection is stable. It follows that when $x = x_0 = \frac{-(1-\gamma)(W-\varepsilon E_3)+(1-\gamma)(y-y\beta+\beta)\alpha\delta L_3}{-(1-\gamma)(1-\alpha)(y-y\beta+\beta)\delta L_3}$ or $y = y_0 = \frac{-(1-\gamma)(W-\varepsilon E_3)+(1-\gamma)(x-x\alpha+\alpha)\beta\delta L_3}{-(1-\gamma)(1-\beta)(x-x\alpha+\alpha)\delta L_3}$, there is $R(z) \equiv 0$. The public's vaccination strategy will not be affected by the evolution of the public health emergency vaccination game system.

Further, $R'(z) = (1-2z)[-(1-\gamma)(W-\varepsilon E_3) + (1-\gamma)(x - x\alpha + \alpha)(y - y\beta + \beta)\delta L_3]$ can be obtained by taking the derivative of $R(z)$. When $x > x_0$ or $y > y_0$, there is $R'(z)|_{z=0} > 0$ and $R'(z)|_{z=1} < 0$. It can be seen that z = 1 (active vaccination strategy) is a stable strategy of the public. When $x < x_0$ or $y < y_0$, there is $R'(z)|_{z=0} < 0$ and $R'(z)|_{z=1} > 0$. It can be seen that z = 0 (passive vaccination strategy) is a stable strategy of the public.

In summary, the evolutionary phase diagram of the vaccination strategy of the public can be obtained (Figure 5). The volume of region V and region VI represent the probability of the public selecting passive vaccination strategy and active vaccination strategy, respectively.

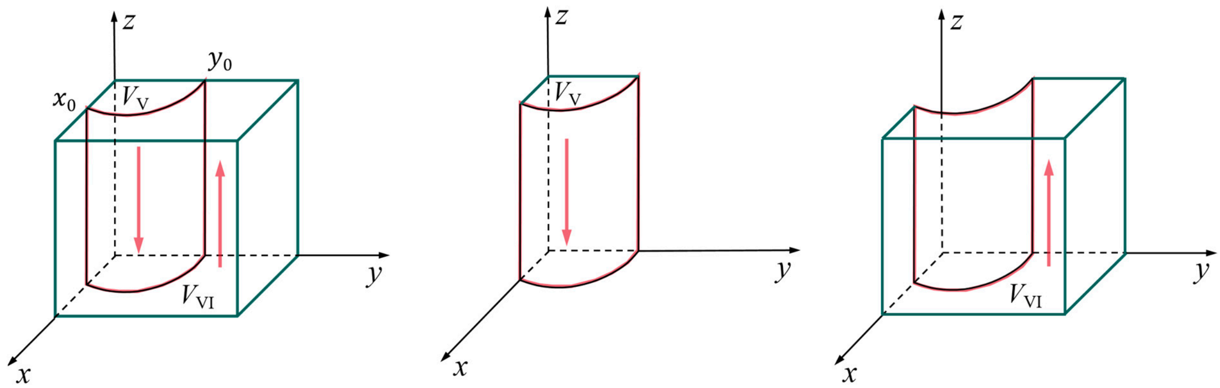


Figure 5. Evolutionary phase diagram of the public's strategies.

3. Simulation Analysis of Public Health Emergency Vaccination Game System

In order to more clearly and accurately describe the influencing factors of the public health emergency vaccination game system and to explore effective measures to promote orderly vaccination in public health emergencies, a numerical simulation analysis is introduced. The influence of the range of vaccination (δ), the diversification of vaccination information release (φ), the level of emergency collaboration between health management departments (θ) and vaccinologists, and the public's awareness of emergency protection (ε) on the evolutionary stability of a health emergency vaccination game system will be analyzed and discussed.

To make the simulation analysis results of the public health emergency vaccination game system close to the actual vaccination situation, based on the Delphi method, five government emergency management personnel, five vaccine developers, and five researchers in the field of public health emergencies were invited to score the initial values of parameters of the public health emergency vaccination game model. Through three rounds of the confirmation and correction of the scoring results, the initial values of the parameters were set as follows: α = 0.7, β = 0.6, γ = 0.5, C_1 = 13, C_2 = 31.5, C_3 = 27, K = 17, W = 19, L_1 = 33, L_2 = 23, L_3 = 21, E_1 = 27, E_2 = 21, E_3 = 23, G_1 = 15, and G_2 = 7.5. It should be noted that the simulation analysis begins with the (0.5,0.5,0.5).

3.1. Analyzing the Influence of the Range of Vaccination (δ)

The range of vaccination (δ) is a variable that describes how widely, to how many people, and at what rate vaccination is implemented. It can be seen that the strategy selections of health management departments, vaccinologists, and the public all have an impact on the vaccination range (δ). When health management departments select a positive promotion strategy, vaccinologists select an active vaccination strategy, and the public selects an active guidance strategy, the range of vaccination has a more direct influence on the public health emergency vaccination game system. Moreover, the range of vaccination is inversely proportional to the perceived losses of health management departments, vaccinologists, and the public in public health emergencies.

When δ = {0.1,0.3,0.5,0.7,0.9}, the evolution trajectory and evolutionary stability state of the public health emergency vaccination game system are as shown in Figure 6. The public health emergency vaccination game system has (1,1,1) and (0,0,0) evolutionarily stable states under different ranges of vaccination. It can be seen that, since the range of vaccination (δ) has an influence on health management departments, vaccinologists, and the public at the same time, the strategy selections of game subjects have a convergence trend under the influence of the range of vaccination.

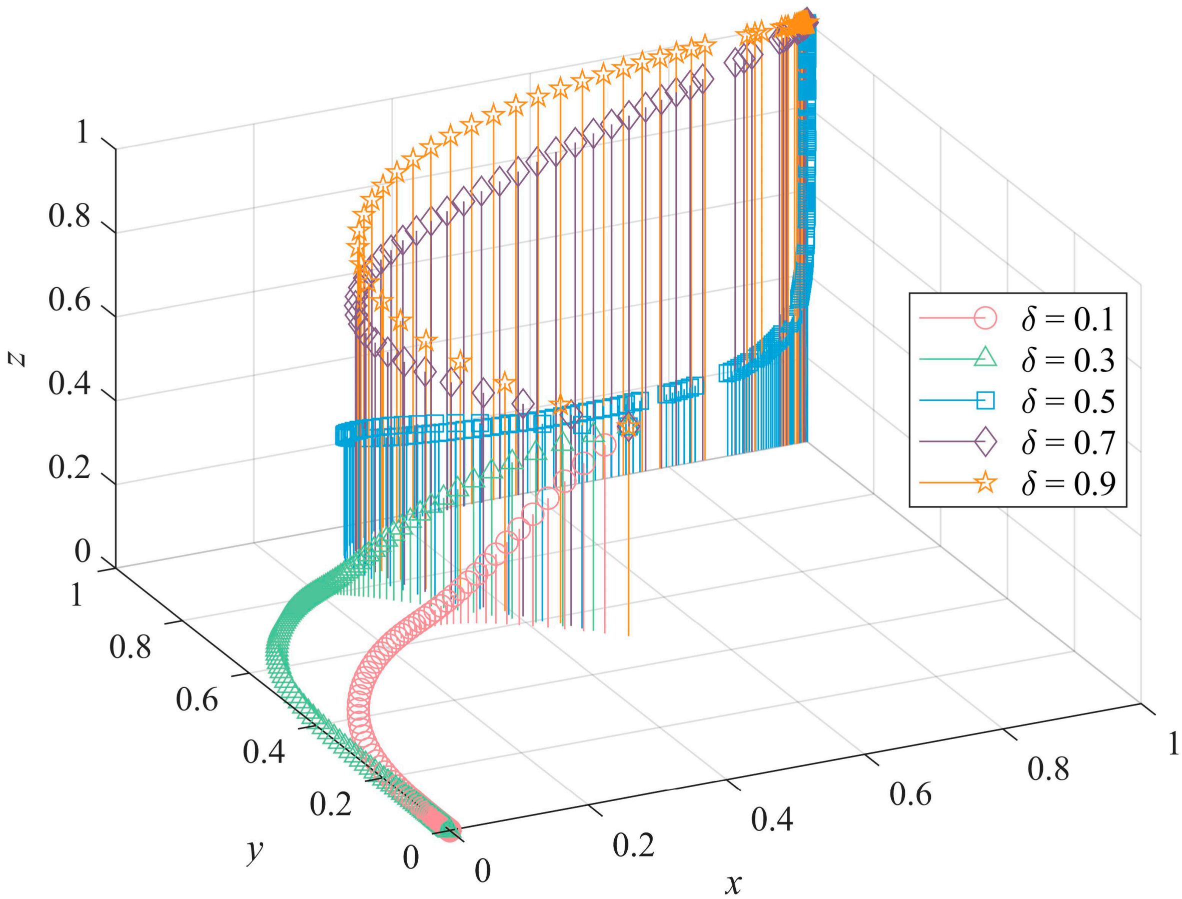


Figure 6. The influence of the range of vaccination (δ).

When $\delta = 0.1$ and $\delta = 0.3$, health management departments, vaccinologists, and the public have lower perceived losses of public health emergencies reduced by vaccination. So, game subjects converge to $x = y = z = 0$. When $\delta = 0.5$, $\delta = 0.7$, and $\delta = 0.9$, the perceived losses of public health emergencies reduced by vaccination are further improved. Moreover, although the implementation costs of vaccination for health management departments will increase with an increase in δ, the public health emergency vaccination game system still converges to (1,1,1).

Figure 7 shows the respective strategy evolution trajectories of health management departments, vaccinologists, and the public obtained via numerical simulation under different ranges of vaccination. When $x = 0$, $y = 0$, and $z = 0$ are stable states of the game system, the convergence rates of stable strategies formed by game subjects are in the order of the public, health management departments, and vaccinologists, from fastest to slowest.

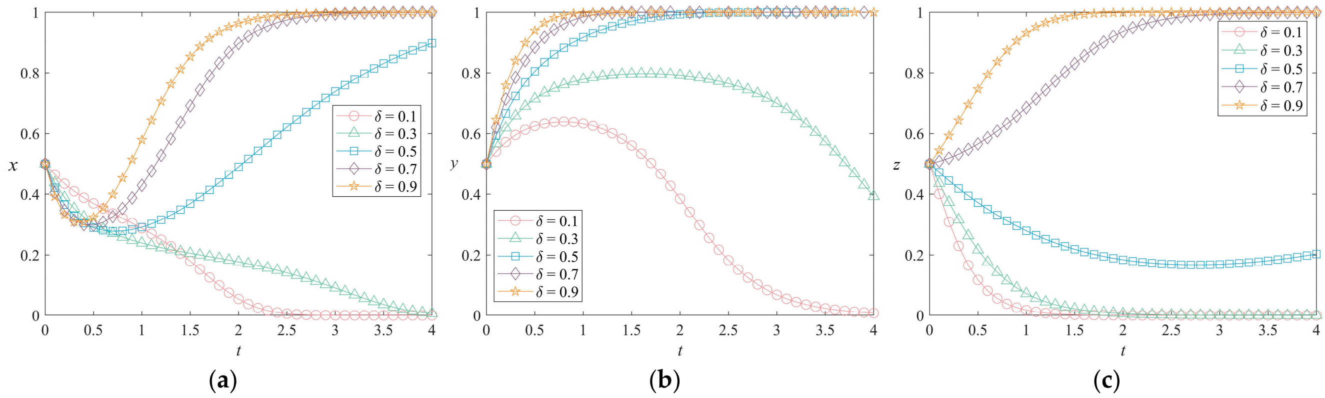


Figure 7. The influence of the range of vaccination (δ) on game subjects. (**a**) Health management departments, (**b**) vaccinologists, and (**c**) the public.

When $x = 1$, $y = 1$, and $z = 1$ are stable states of the game system, the convergence rate of vaccinologists' strategy evolution trajectory is the fastest. At the same time, it can be seen that when $\delta = 0.1$ and $\delta = 0.3$, there is a cross phenomenon in the strategy evolution trajectories of health management departments. In the early stage of evolution, health management departments with larger δ are more inclined to select a negative promotion strategy. When $\delta = 0.5$, $\delta = 0.7$, and $\delta = 0.9$, the health management departments evolved to $x = 0$ first. With an increase in evolution time, health management departments tended to converge to $x = 1$ and finally stabilized. This is mainly due to the increasing costs to health management departments of developing vaccination planning and promoting the implementation of vaccination. To a certain extent, this dissuaded health management departments from selecting a positive promotion strategy.

3.2. Analyzing the Influence of the Diversification of Vaccination Information Release (φ)

The diversification of vaccination information release (φ) represents not only the richness of the types of vaccination information (vaccine classification, vaccination methods, applicable groups, and precautions), but also the diversification of vaccination information release channels (press conferences, information disclosure, and online questions and answers). Therefore, the diversification of vaccination information release requires financial support from health management departments and vaccinologists. Moreover, the diversification of vaccination information release will bring about more benefits to health management departments and vaccinologists.

The impact of the diversification of vaccination information release on the public health emergency vaccination game system is shown in Figure 8. With an increase in the diversification of vaccination information release, the stable strategy combinations of the public health emergency vaccination game system are (0,1,0), (0,0,0), and (1,1,1), in that order. When $\varphi = 0.1$, health management departments have lower perceived benefits and higher costs, while vaccinologists incur lower costs when encouraging vaccination. At this time, a negative promotion strategy, an active guidance strategy, and a passive vaccination strategy are the stable strategy selections of game subjects. When $\varphi = 0.3$, vaccinologists' costs for guiding the public to participate in vaccination and introducing vaccine-related information will further increase, and their inclination to select a passive guidance strategy will dominate. The public health emergency vaccination game system eventually converges to (0,0,0). When φ is further increased to 0.5, 0.7, and 0.9, the perceived benefits of health management departments, vaccinologists, and the public are all at a higher level, which can drive the game system to form a stable state of (1,1,1).

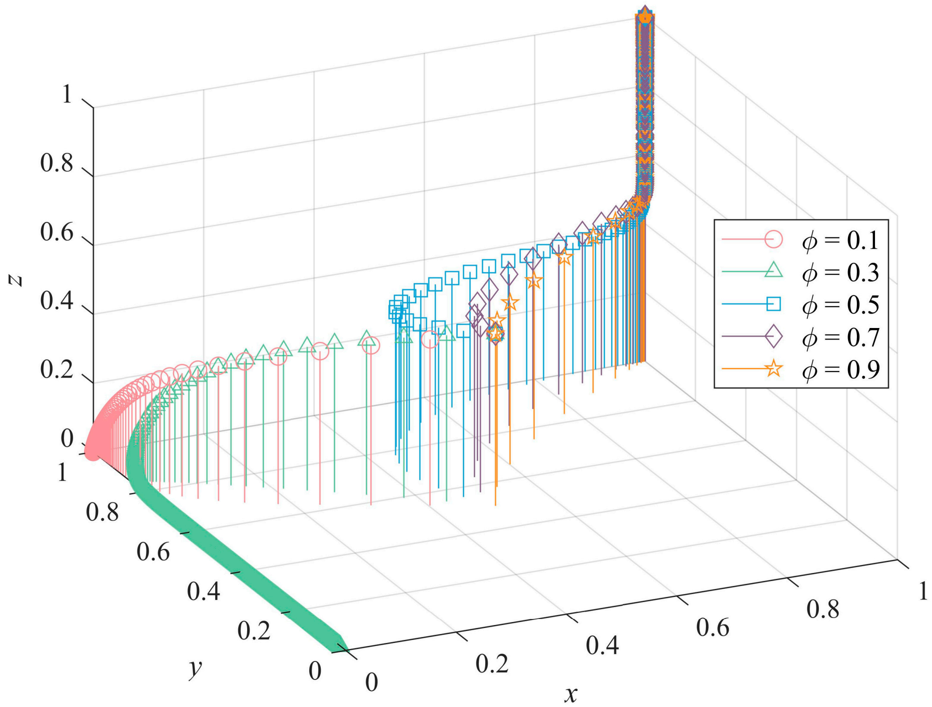
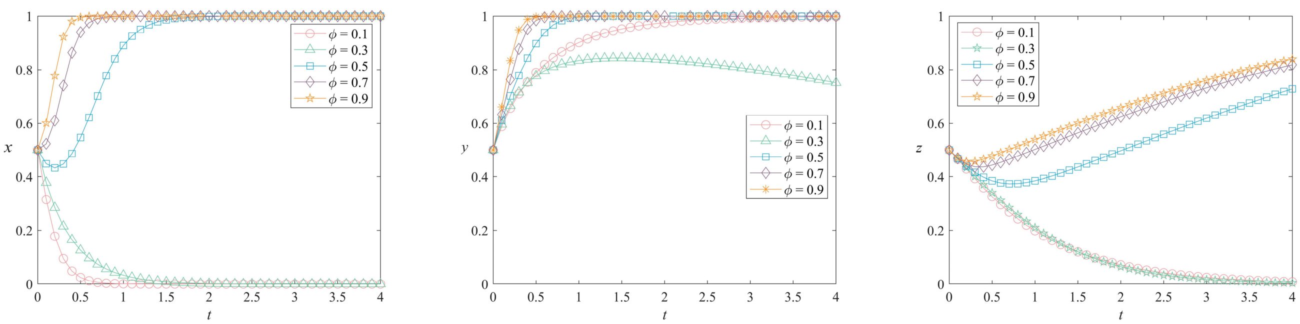


Figure 8. The influence of the diversification of vaccination information release (φ).

The influence of the diversification of vaccination information release on the strategy selection of health management departments, vaccinologists, and the public is shown in Figure 9. By comparing Figure 9a–c, it can be found that when the stable state of the public health emergency vaccination game system is (1,1,1), the convergence rates of health management departments and vaccinologists are faster, while the evolution trajectory of the public to the stable state is smoother. At the same time, with an increase in φ, the evolution time for health management departments and vaccinologists to reach a stable strategy became shorter. In addition, comparing Figure 9a,b, it can be seen that health management departments have invested more in enhancing the diversity of vaccination information releases. When $\varphi = 0.1$, health management departments form a stable state of $x = 0$, while vaccinologists converge towards $y = 1$. Further, it can be seen from Figure 9b that with an increase in φ, the stable strategy selection of vaccinologists changed from an active guidance strategy to a passive guidance strategy, and then back to an active guidance strategy. This is because the diversification of vaccination information release not only affects communication costs, but also enhances the reputation benefits obtained by vaccinologists.



(**a**) (**b**) (**c**)

Figure 9. The influence of the diversification of vaccination information release (φ) on game subjects. (**a**) Health management departments, (**b**) vaccinologists, and (**c**) the public.

3.3. Analyzing the Influence of the Level of Emergency Collaboration between Health Management Departments and Vaccinologists (θ)

The level of emergency collaboration between health management departments and vaccinologists (θ) is related to the level of trust, docking channels, and information sharing among subjects, which can be improved through cooperation in public health emergencies and vaccine research and development. The higher the level of emergency collaboration, the lower the costs health management departments and vaccinologists incur for vaccination. Figure 10 shows the evolution trajectory of the public health emergency vaccination game system obtained using a simulation analysis when the level of emergency collaboration (θ) was 0.1, 0.3, 0.5, 0.7, and 0.9.

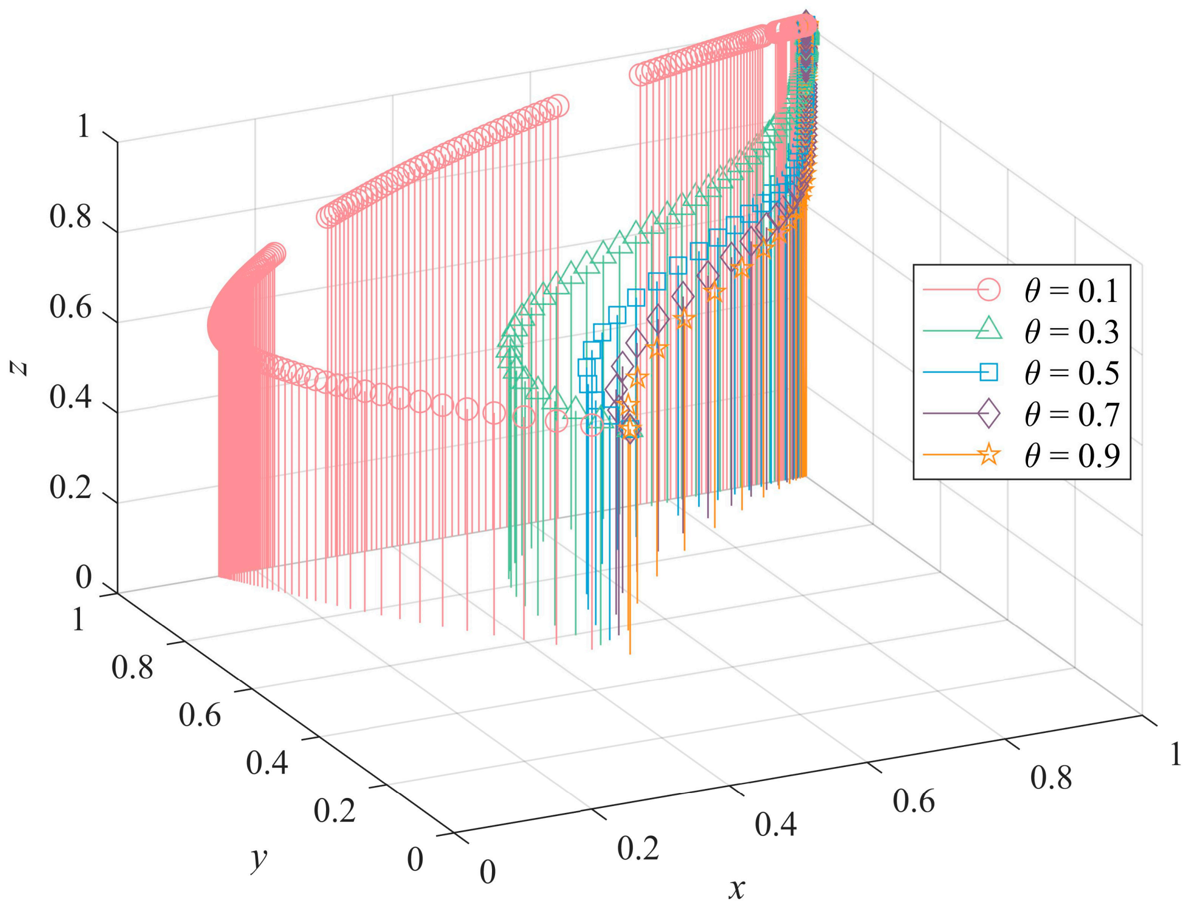
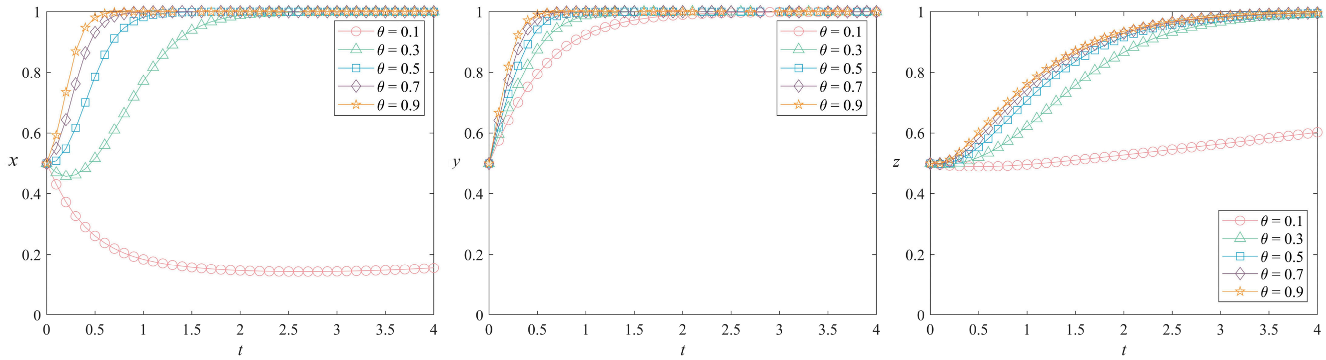


Figure 10. The influence of the level of emergency collaboration (θ).

The influence of the level of emergency collaboration on the public health emergency vaccination game is mainly reflected in the difference in the speed of evolution to the stable state (1,1,1). It can be seen that enhancing the level of emergency collaboration between health management departments and vaccinologists has a positive driving effect on public health emergency vaccination. Specifically, as the level of emergency collaboration (θ) increases, the game system's evolution to a stable state becomes shorter. Moreover, when $\theta = \{0.3, 0.5, 0.7, 0.9\}$, it can be seen that the evolution time for health management departments and vaccinologists to reach $x = 1$ and $y = 1$ is earlier than that for the public to reach $z = 1$.

Although $x = 1$, $y = 1$, and $z = 1$ are all stable states of the public health emergency vaccination game system with different levels of emergency collaboration, the path and rate of game subjects' evolution to the stable state are not consistent. Correspondingly, Figure 11 shows the differentiated evolution trajectories of health management departments, vaccinologists, and the public toward the vaccination game system's stable state

(1,1,1). According to Figures 10 and 11a, when $\theta = 0.1$, although health management departments are more inclined to select a negative promotion strategy during the initial stage of evolution, it will converge to $x = 1$ by the end. As the level of emergency collaboration increased, the costs to health management departments and vaccinologists of informing the public about vaccination and responding to vaccination issues decreased. Therefore, health management departments and vaccinologists are more willing to select a positive promotion strategy and an active guidance strategy. The evolution speed and time of strategy evolution to the stable state are faster and shorter, respectively. In addition, although the level of emergency collaboration has a direct effect on the public's strategy selection, both the public convergence to $z = 1$ and the evolution speed gradually accelerated under the influence of health management departments and vaccinologists in the game system.



(**a**) (**b**) (**c**)

Figure 11. The influence of the level of emergency collaboration (θ) on game subjects. (**a**) Health management departments, (**b**) vaccinologists, and (**c**) the public.

3.4. Analyzing the Influence of the Public's Awareness of Emergency Protection (ε)

The public's awareness of emergency protection (ε) indicates the public's awareness of the transmission route of a virus, protective measures that can be taken, and other vaccination-related matters. Moreover, the public's awareness of emergency protection not only describes the self-rescue and protection ability at the individual level, but also the overall sense of safety. Therefore, the public's awareness of emergency protection will affect the vaccination rate and the game subjects' perceived benefits from vaccination.

Under different levels of awareness of emergency protection, the differences in the stable strategies and evolution paths of the public health emergency vaccination game system are as shown in Figure 12. With an increase in ε, the stable state of the public health emergency vaccination game system changes from (0,0,0) to (1,1,1). When a public health emergency is not occurring, cultivating and strengthening the public's awareness of emergency protection measures can build preparedness and improve the effectiveness of emergency responses.

Further, the simulation analysis results of the impact of the public's awareness of emergency protection on the strategy selections of health management departments, vaccinologists, and the public are as shown in Figure 13. It can be seen that, when $\varepsilon = 0.1$ and $\varepsilon = 0.3$, the public converges to the stable state faster. For $\varepsilon = 0.5$, $\varepsilon = 0.7$, and $\varepsilon = 0.9$, vaccinologists converge to the stable state faster than health management departments and the public. This is mainly because the active guidance of vaccinologists and a high level of public awareness of emergency protection will improve the efficiency of dealing with public health emergencies. Therefore, the response rate of health management departments that select a positive promotion strategy is relatively slow. Moreover, it can be seen from Figure 13a that, when health management departments eventually converge to $x = 1$, there is a short-term evolution trend of negative promotion strategy at the initial stage. Similarly, Figure 13b shows that when vaccinologists eventually converge to $y = 0$, there is an evolution trend toward the active guidance strategy at the initial stage. In addition, the study found that the impact of ε on the public is more direct, which shows that the strategy evolution trajectories of the public corresponding to different ε are more separated. This also shows that the greater the awareness of emergency protection, the more the public can make accurate judgments about public health emergencies, viruses, and vaccination.

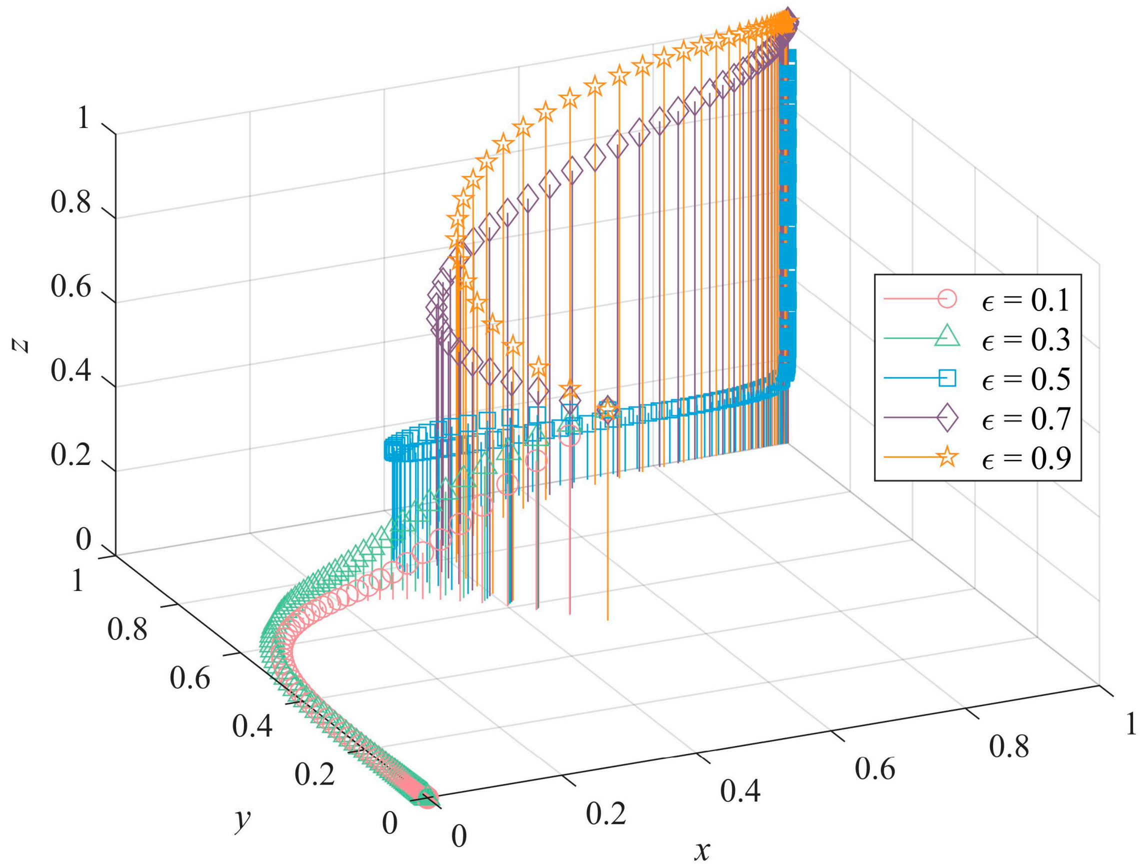


Figure 12. The influence of the public's awareness of emergency protection (ε).

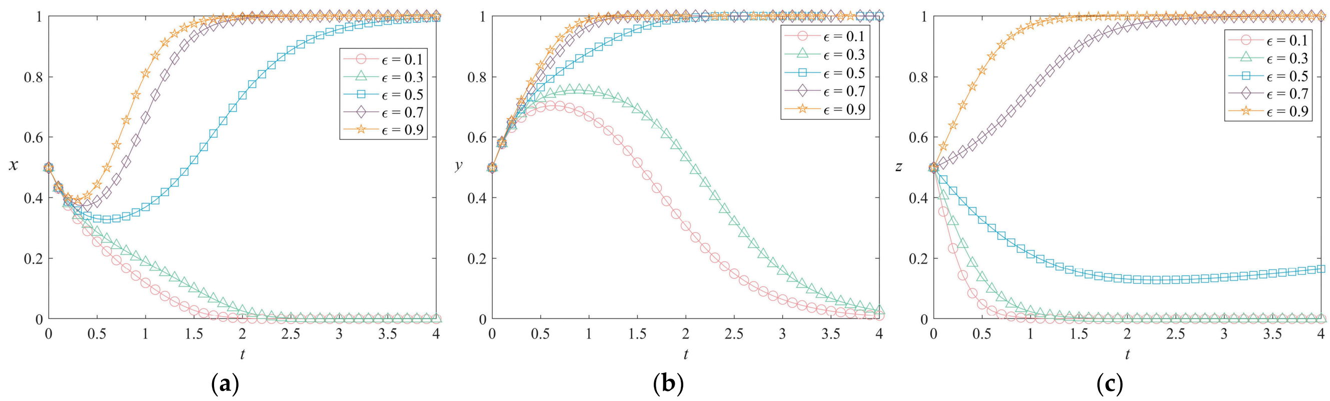


Figure 13. The influence of the public's awareness of emergency protection (ε) on game subjects. (**a**) Health management departments, (**b**) vaccinologists, and (**c**) the public.

4. Discussion

It is an important responsibility of governments and health management departments to promote vaccination in public health emergencies. This also requires the cooperation of vaccinologists and the participation of the public to improve the vaccination rate and coverage. This study constructed a public health emergency vaccination game system based on health management departments, vaccinologists, and the public. Then, the influencing factors of a public health emergency vaccination game system were analyzed.

The simulation results show that δ, φ, θ, and ε can all promote the evolution of the vaccination game system to the stable state of (1,1,1). This shows that the range of vaccination, the diversification of vaccination information release, the level of emergency collaboration between health management departments and vaccinologists, and the public's awareness of emergency protection can effectively promote and strengthen the implementation of vaccination. Since health management departments need to cover various costs in public health emergency vaccination, such as those of vaccine research and development, organization of vaccination, and responses to vaccine-related situations, the evolution trajectories of health management departments' strategy selection in the simulation analysis are complicated.

Vaccinologists, with their efforts to engage the public in vaccination and being given support and incentives from health management departments, usually have an active initial guidance strategy ($y = 1$) in the public health emergency vaccination game system. Because the public are the passive party in the process of public health emergency vaccination, the stable state of the active vaccination strategy ($z = 1$) lags behind that of health management departments and vaccinologists. Moreover, although high levels of δ, φ, θ, and ε can encourage game subjects to form a strategy combination of a positive promotion strategy, an active guidance strategy, and an active vaccination strategy, the evolution trajectories of game subjects' strategy selection are not consistent.

With an increase in the range of vaccination (δ), the evolution trajectories of health management departments' strategy selection fluctuate. When $\delta = 0.1$, the evolution rate of health management departments to $x = 0$ is slower than that of $\delta = \{0.3,0.5,0.7,0.9\}$. This is mainly due to the small range of vaccination and the low costs paid by health management departments to organize vaccination. With an increase in δ, the implementation costs of vaccination will increase, but at the same time, more emergency benefits will be gained and a perception of loss reduction will be achieved.

With an increase in the diversification of vaccination information release, the convergence direction of vaccinologists changed from $y = 1$ to $y = 0$ and then back to $y = 1$. This is because the diversification of vaccination information release increased the communication costs paid by vaccinologists. Therefore, when $\varphi = 0.3$, the passive guidance strategy became the stable strategy. When $\varphi = \{0.5,0.7,0.9\}$, the increase in reputation benefits obtained by vaccinologists and the influence of other game subjects' strategy selection made vaccinologists converge towards $y = 1$.

Regardless of changes in the level of emergency collaboration between health management departments and vaccinologists, the evolutionarily stable states of public health emergency vaccination game systems are (1,1,1). With an increase in θ, the evolution speed of game subjects towards (1,1,1) was faster and the evolution time was shorter. Among them, vaccinologists were the fastest to form a stable state, followed by health management departments, while the public was relatively slow.

The public's awareness of emergency protection had a direct impact on the public's strategy selection. Moreover, the higher the public's awareness of emergency protection, the higher the implementation costs. In this situation, although the implementation costs of health management departments were higher, they still adopted a positive promotion strategy. Vaccinologists also communicated more smoothly with the public, which made them more inclined to select an active guidance strategy.

From the above analysis, it can be seen that exploring how to effectively promote the implementation of vaccination from the perspective of an inter-organizational game system is of great significance for improving the vaccination rate, reducing the influence range of a virus, and preventing and controlling public health emergencies. Targeted optimization strategies can be formulated based on the influencing factors analyzed in this study. In general, the practical and theoretical contributions of this study include identifying the types of subjects involved in public health emergency vaccination and deconstructing the problems with promoting vaccination based on the interactions between subjects. A public health emergency vaccination game model was constructed by introducing EGT. Moreover, the main factors affecting the promotion of vaccination were discussed and clarified by interpreting the evolution rules of the strategy selection of health management departments, vaccinologists, and the public. This provided a basis for understanding how to promote vaccination from the perspective of inter-organizational interaction.

There are some limitations to this study. The research scheme can still be expanded, as the list of game subjects can be expanded, by introducing health management departments at different levels and functions. Additionally, we assumed bounded rationality among health management departments, vaccinologists, and the public based on evolutionary game theory. This can be done by introducing other theories to analyze the factors affecting vaccination decisions such as misinformation, political influences, and personal beliefs. Improving the efficiency of vaccination is as crucial as promoting its implementation. In the future, relevant studies can consider the entire process of vaccine management and clarify the main factors affecting the efficiency of vaccination, including various aspects such as research and development, production, storage, and transportation, so as to provide a reference for vaccination practice. Moreover, it is important to consider the dynamic and evolving nature of public health emergencies. In the next stage, comparative studies on vaccination at different stages of public health emergencies can be further carried out.

5. Conclusions and Implications

5.1. Overall Conclusions

Timely vaccination is key to effectively block the spread of viruses and reduce losses during public health emergencies. Vaccination involves the participation and cooperation of multiple subjects. Clarifying the interaction between multiple subjects in the promotion of vaccination and analyzing the key factors blocking the collaboration of multiple subjects are important for improving the efficiency and expanding the coverage of vaccination. This study constructed a public health emergency vaccination game system using EGT and clarified the factors that affect the operation of a game system and the strategy selection of game subjects. The overall conclusions can be condensed as follows:

(1) The range of vaccination, diversification of vaccination information release, level of emergency collaboration, and public's awareness of emergency protection can all contribute to the formation of a public health emergency vaccination game system with a positive promotion strategy, active guidance strategy, and active vaccination strategy, which can effectively promote vaccination.

(2) The range of vaccination affected both the costs of health management departments and the perceived losses of health management departments in public health emergencies. The diversification of vaccination information release has an impact on the costs to health management departments and vaccinologists, and also affects the emergency and vaccination benefits of health management departments and vaccinologists. Therefore, the influences of the range of vaccination and the diversification of vaccination information release on the strategy evolution of game subjects have two sides, and game trajectories have a tendency to exhibit fluctuation and repetition.

(3) The level of emergency collaboration between health management departments and vaccinologists can reduce the costs of implementing vaccination. Collaboration can also enhance the enthusiasm of health management departments and vaccinologists to select a positive promotion strategy and an active guidance strategy.

(4) A high level of public awareness of emergency protection can enhance the public's understanding of viruses associated with public health emergencies and can increase their resolve to participate in vaccination. In addition, the higher the public's awareness of emergency protection, the easier it is for health management departments and vaccinologists to publicize vaccine knowledge and answer vaccination-related questions.

(5) When (1,1,1) is the stable state of the public health emergency vaccination game system, the convergence speed of health management departments and vaccinologists to form a stable strategy is greater than that of the public. This indicates that, although

the public lags behind in selecting the active vaccination strategy, they may have increased enthusiasm for participating in vaccination due to the promotion strategies of health management departments and vaccinologists. Correspondingly, vaccination rates and coverage can also be improved.

5.2. Further Implications

Based on the overall conclusions and the simulation results of the public health emergency vaccination game system, this study has implications for improving vaccination strategy, strengthening vaccination collaboration, mobilizing the enthusiasm of vaccinologists, and enhancing the initiative of the public. In general, it can provide a decision-making reference for promoting the effective implementation of vaccination.

(1) Improving vaccination plans and strategies. Systematic and complete vaccination strategies guarantee the orderly implementation of vaccination. Therefore, the first step is to improve strategies pertaining to important matters such as clearing the target population, selecting a vaccine, and setting vaccination requirements according to the transmission characteristics of the virus. Moreover, a differentiated management plan for vaccination can be developed and implemented for high-risk groups and the general population. Secondly, continuous attention should be paid to the progress and effectiveness of vaccination. According to vaccine research, combined with knowledge of public health emergencies and virus mutation, the vaccination strategy should be adjusted to respond to the whole-cycle characteristics of public health emergencies. Thirdly, it is necessary to improve the whole-process traceability system of vaccines and the safety supervision to strengthen the process management and ensure efficient and smooth development, production, transportation, and delivery of vaccines.

(2) Strengthening cross-departmental collaboration for vaccination. Cross-departmental collaboration (via, e.g., response linkage and working consultation) is important to support the implementation of vaccination. Specifically, it is necessary to strengthen the collaboration between upper and lower departments. Health management departments at higher levels should strengthen overall planning and coordination, and guide health management departments at lower levels to organize and implement vaccination work. Additionally, health management departments should provide guidance to local disease control departments, communities, and hospitals, and emphasize the responsibility of vaccination. It is also necessary to strengthen the collaboration between different functional departments. Vaccine research and development, production, transportation, and delivery—as well as supply, supervision, and other safeguarding measures—require the participation of multiple departments. For example, in the process of vaccine research and development, the collaboration of science and technology management departments, health management departments, and scientific research institutions is needed. In the process of vaccination, the collaboration of health management departments, communities, and hospitals is needed. In the process of vaccine safety supervision, the collaboration of health administration departments, drug administration departments, and market supervision departments is needed. In addition, the Chinese government has promoted a nationwide information system for vaccination and cross-departmental collaboration on vaccination at the data level, which is also worthy of note.

(3) Mobilizing the enthusiasm of vaccinologists to participate in vaccination. Increasing the enthusiasm of vaccinologists to guide the public to participate in vaccination is important to promote the implementation of vaccination. Health management departments and related departments should provide incentives and platforms for vaccinologists. They should communicate with vaccinologists in a timely manner, fully respect their professional expertise, and listen to their suggestions about the implementation of vaccination. Moreover, commendation should be given to vaccinologists publicly so as to enhance their authority and reputation. Health management departments should build diversified communication platforms for vaccinologists

to guide the public to participate in vaccination. For example, vaccinologists can be invited to participate in cross-departmental consultation meetings and vaccination press conferences. Teams of vaccinologists can also be established to provide on-site guidance for the implementation of vaccination. Through the above measures, vaccinologists can be more involved in vaccination during public health emergencies.

(4) Encouraging the public's initiative to participate in vaccination. The eagerness of the public to participate in vaccination is not only related to self-motivation, but also to the way government departments release vaccination information. Firstly, it is necessary to cultivate the public's awareness about the means of protection against viruses and other public health emergencies in daily life. This can help to strengthen a whole population's grasp of health knowledge and improve risk perception, information assessment, and self-protection abilities. Secondly, during public health emergencies, it is necessary to publicize vaccination knowledge, policy interpretations, and vaccination trends via various media such as public announcements, posters, education manuals, and short publicity videos, to maximize the different channels by which the public can obtain information about vaccination. Moreover, government departments can release information mainly through official channels and coordinate follow-up through multiple media platforms. Thirdly, organization and management of vaccination implementation should be improved. The vaccination location should be reasonable, the number of vaccination personnel should be appropriate, and vaccination appointments should be reservable online in advance to make public participation as convenient as possible.

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References

1. Assefa, Y.; Gilks, C.F.; Reid, S.; van de Pas, R.; Gete, D.G.; Van Damme, W. Analysis of the COVID-19 pandemic: Lessons towards a more effective response to public health emergencies. *Glob. Health* **2022**, *18*, 10. [CrossRef]
2. Dryhurst, S.; Schneider, C.R.; Kerr, J.; Freeman, A.L.J.; Recchia, G.; van der Bles, A.M.; Spiegelhalter, D.; van der Linden, S. Risk perceptions of COVID-19 around the world. *J. Risk Res.* **2020**, *23*, 994–1006. [CrossRef]
3. Bryce, C.; Ring, P.; Ashby, S.; Wardman, J.K. Resilience in the face of uncertainty: Early lessons from the COVID-19 pandemic. *J. Risk Res.* **2020**, *23*, 880–887. [CrossRef]
4. Liu, J.; Dong, C.; An, S.; Mai, Q. Dynamic Evolution Analysis of the Emergency Collaboration Network for Compound Disasters: A Case Study Involving a Public Health Emergency and an Accident Disaster during COVID-19. *Healthcare* **2022**, *10*, 500. [CrossRef]
5. Liu, J.; Dong, C. Cross-departmental emergency coordination characteristics formed by multiple risks: Evidence from production safety special emergency campaigns across government levels in China. *Int. J. Disaster Risk Reduct.* **2024**, *111*, 104672. [CrossRef]
6. Kerr, S.; Bedston, S.; Cezard, G.; Sampri, A.; Murphy, S.; Bradley, D.T.; Morrison, K.; Akbari, A.; Whiteley, W.; Sullivan, C.; et al. Undervaccination and severe COVID-19 outcomes: Meta-analysis of national cohort studies in England, Northern Ireland, Scotland, and Wales. *Lancet* **2024**, *403*, 554–566. [CrossRef]
7. Notarte, K.I.; Catahay, J.A.; Velasco, J.V.; Pastrana, A.; Ver, A.T.; Pangilinan, F.C.; Peligro, P.J.; Casimiro, M.; Guerrero, J.J.; Gellaco, M.M.L.; et al. Impact of COVID-19 vaccination on the risk of developing long-COVID and on existing long-COVID symptoms: A systematic review. *eClinicalMedicine* **2022**, *53*, 101624. [CrossRef]
8. Macklin, G.R.; Peak, C.; Eisenhawer, M.; Kurji, F.; Mach, O.; Konz, J.; Gast, C.; Bachtiar, N.S.; Bandyopadhyay, A.S.; Zipursky, S. Enabling accelerated vaccine roll-out for Public Health Emergencies of International Concern (PHEICs): Novel Oral Polio Vaccine type 2 (nOPV2) experience q. *Vaccine* **2023**, *411*, A122–A127. [CrossRef]

9. Najjar-Debbiny, R.; Gronich, N.; Khoury, J.; Amar, M.; Stein, N.; Goldstein, L.H.; Saliba, W. Effectiveness of Paxlovid in Reducing Severe Coronavirus Disease 2019 and Mortality in High-Risk Patients. *Clin. Infect. Dis.* **2023**, *76*, 1158–1159. [CrossRef]
10. Utami, A.M.; Rendrayani, F.; Khoiry, Q.A.; Noviyanti, D.; Suwantika, A.A.; Postma, M.J.; Zakiyah, N. Economic evaluation of COVID-19 vaccination: A systematic review. *J. Glob. Health* **2023**, *13*, 06001. [CrossRef]
11. Watson, O.J.; Barnsley, G.; Hogan, A.B.; Winskill, P.; Ghani, A.C. Global impact of the first year of COVID-19 vaccination: A mathematical modelling study (vol 22, pg 1293, 2022). *Lancet Infect. Dis.* **2023**, *23*, E400. [CrossRef]
12. Li, J.; Zhang, Y.; Zhang, X.; Liu, L. Influenza and Universal Vaccine Research in China. *Viruses* **2023**, *15*, 116. [CrossRef]
13. Shah, A.; Coiado, O.C. COVID-19 vaccine and booster hesitation around the world: A literature review. *Front. Med.* **2023**, *9*, 1054557. [CrossRef]
14. Wang, G.; Yao, Y.; Wang, Y.; Gong, J.; Meng, Q.; Wang, H.; Wang, W.; Chen, X.; Zhao, Y. Determinants of COVID-19 vaccination status and hesitancy among older adults in China. *Nat. Med.* **2023**, *29*, 623. [CrossRef]
15. Chen, S.; Zhang, Z.; Yang, J.; Wang, J.; Zhai, X.; Barnighausen, T.; Wang, C. Fangcang shelter hospitals: A novel concept for responding to public health emergencies. *Lancet* **2020**, *395*, 1305–1314. [CrossRef]
16. Wei, J.; Wang, L.; Yang, X. Game analysis on the evolution of COVID-19 epidemic under the prevention and control measures of the government. *PLoS ONE* **2020**, *15*, e0240961. [CrossRef]
17. Hong, S. COVID-19 vaccine communication and advocacy strategy: A social marketing campaign for increasing COVID-19 vaccine uptake in South Korea. *Humanit. Soc. Sci. Commun.* **2023**, *10*, 109. [CrossRef]
18. Zhou, Y.; Zhang, J.; Yang, Y. Navigating Resource Challenges in Health Emergencies: The Role of Information Diffusion and Virus Spread in Demand Dynamics. *Systems* **2024**, *12*, 95. [CrossRef]
19. Firouzabadi, N.; Ghasemiyeh, P.; Moradishooli, F.; Mohammadi-Samani, S. Update on the effectiveness of COVID-19 vaccines on different variants of SARS-CoV-2. *Int. Immunopharmacol.* **2023**, *117*, 109968. [CrossRef] [PubMed]
20. Ceban, F.; Kulzhabayeva, D.; Rodrigues, N.B.; Di Vincenzo, J.D.; Gill, H.; Subramaniapillai, M.; Lui, L.M.W.; Cao, B.; Mansur, R.B.; Ho, R.C.; et al. COVID-19 vaccination for the prevention and treatment of long COVID: A systematic review and meta-analysis. *Brain Behav. Immun.* **2023**, *111*, 211–229. [CrossRef]
21. Rai, R.K.; Tiwari, P.K.; Khajanchi, S. Modeling the influence of vaccination coverage on the dynamics of COVID-19 pandemic with the effect of environmental contamination. *Math. Methods Appl. Sci.* **2023**, *46*, 12425–12453. [CrossRef]
22. Niu, Y.; Tao, Z.; Zhang, H. Dynamics of Interagency Networks under Stress in Public Health Emergencies: Evidence from China. *Public Perform. Manag.* **2022**, *45*, 799–827. [CrossRef]
23. Liu, J.; Song, Y.; An, S.; Dong, C.; Lian, C. Exploring time evolution characteristics of the collaborative mode in emergency information release of public health emergencies: A network analysis of response to COVID-19 from the central government of China. *Front. Public Health* **2022**, *10*, 970514. [CrossRef]
24. Kamran, M.A.; Kia, R.; Goodarzian, F.; Ghasemi, P. A new vaccine supply chain network under COVID-19 conditions considering system dynamic: Artificial intelligence algorithms. *Socio-Econ. Plan. Sci.* **2023**, *85*, 101378. [CrossRef]
25. Lazarus, J.V.; Wyka, K.; White, T.M.; Picchio, C.A.; Gostin, L.O.; Larson, H.J.; Rabin, K.; Ratzan, S.C.; Kamarulzaman, A.; El-Mohandes, A. A survey of COVID-19 vaccine acceptance across 23 countries in 2022. *Nat. Med.* **2023**, *29*, 366–375. [CrossRef] [PubMed]
26. Whitehead, H.S.; French, C.E.; Caldwell, D.M.; Letley, L.; Mounier-Jack, S. A systematic review of communication interventions for countering vaccine misinformation. *Vaccine* **2023**, *41*, 1018–1034. [CrossRef]
27. Bergen, N.; Kirkby, K.; Fuertes, C.V.; Schlotheuber, A.; Menning, L.; Mac Feely, S.; O'Brien, K.; Hosseinpoor, A.R. Global state of education-related inequality in COVID-19 vaccine coverage, structural barriers, vaccine hesitancy, and vaccine refusal: Findings from the Global COVID-19 Trends and Impact Survey. *Lancet Glob. Health* **2023**, *11*, E207–E217. [CrossRef]
28. Liu, J.; Dong, C. Understanding the Complex Adaptive Characteristics of Cross-Regional Emergency Collaboration in China: A Stochastic Evolutionary Game Approach. *Fractal Fract.* **2024**, *8*, 98. [CrossRef]
29. Dong, C.; Liu, J.; Mi, J. Information-Driven Integrated Healthcare: An Analysis of the Cooperation Strategy of County Medical Community Based on Multi-Subject Simulation. *Healthcare* **2023**, *11*, 2019. [CrossRef]
30. Dong, C.; Liu, J.; Mi, J. How to Enhance Data Sharing in Digital Government Construction: A Tripartite Stochastic Evolutionary Game Approach. *Systems* **2023**, *11*, 212. [CrossRef]
31. Ouyang, Y.; Zhao, H. Evolutionary Game Analysis of Collaborative Prevention and Control for Public Health Emergencies. *Sustainability* **2022**, *14*, 15089. [CrossRef]
32. Xiao, Y.; Peng, Q.; Xu, W. Evolutionary Game Analysis of Cross-Regional Coordinated Governance of Major Public Health Emergencies: The Example of the Spread of the COVID-19 Outbreak. *Math. Probl. Eng.* **2021**, *2021*, 9992163. [CrossRef]
33. Nan, R.; Chen, J.; Zhu, W. Evolutionary game analysis of multiple subjects in the management of major public health emergencies. *Heliyon* **2024**, *10*, e29823. [CrossRef]
34. Yuan, Y.; Du, L.; Luo, L.; Cui, L. Allocation strategy of medical supplies during a public health emergency: A tripartite evolutionary game perspective. *Sci. Rep.* **2023**, *13*, 9571. [CrossRef]
35. Cao, F.; Zhang, L.; Wu, Y. The Whistleblower's Dilemma: An Evolutionary Game Analysis of the Public Health Early Warning System. *Discret. Dyn. Nat. Soc.* **2022**, *2022*, 5796428. [CrossRef]
36. Wang, Y.; Qi, L.; Cai, S. How can the collaborative participation of regulators, whistleblowers, and parties effectively promote rumor management in public health emergencies? *Front. Public Health* **2024**, *12*, 1399905. [CrossRef]

37. Chen, L.; Li, H.; Tian, F.; Xie, C.; Zhao, L. Research on Psychological Crisis Intervention Strategies under Emergencies: An Analysis Based on the Four-Party Evolutionary Game. *Sustainability* **2023**, *15*, 15226. [CrossRef]
38. Liu, J.; Dong, C.; An, S. Integration and modularization: Research on urban cross-regional emergency cooperation based on the network approach. *Int. J. Disaster Risk Reduct.* **2022**, *82*, 103375. [CrossRef]
39. Fan, R.; Wang, Y.; Lin, J. Study on Multi-Agent Evolutionary Game of Emergency Management of Public Health Emergencies Based on Dynamic Rewards and Punishments. *Int. J. Environ. Res. Public Health* **2021**, *18*, 8278. [CrossRef]
40. Lu, B.; Zhu, L. Public health events emergency management supervision strategy considering citizens' and new media's different ways of participation. *Soft Comput.* **2022**, *26*, 11749–11769. [CrossRef]
41. Zhao, Y.; Jiang, Y.; Zhang, W.; Zhu, Y. Relationship between Risk Perception, Emotion, and Coping Behavior during Public Health Emergencies: A Systematic Review and Meta-Analysis. *Systems* **2023**, *11*, 181. [CrossRef]