The Whistleblower's Dilemma: An Evolutionary Game Analysis of Early Warning System for Public Health Emergency

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The Whistleblower’s Dilemma: An Evolutionary Game Analysis of Early Warning System for Public Health Emergency

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Abstract: The outbreak of a disease is presenting a serious challenge to China’s current public health emergency management system. Despite of China’s emergency preparedness is showing a good overall progress, gaps remain in the implementation of effective early warning system. In this context, a tripartite evolutionary game model composed of the local government, the whistleblower, and the public is formulated. By using MATLAB, the dynamic evolution path of the game model is stimulated under different conditions. The stable strategies for early warning system for public health emergency are also explored. The results indicate that the cost of whistleblowing, the cost of response, and the benefit of attention significantly influence strategic decisions among three parties. This study highlights the importance of the whistleblowing in managing public health emergency. Yet our findings provide theoretical support for policy recommendations for promoting the public health emergency preparedness.

Keywords: pandemic; whistleblower; early warning system; public health emergency; evolutionary game
1 Introduction

The outbreak of a disease not only has a huge impact on socioeconomic order and people's safety and property, but also brings severe challenges to the public health emergency management system in China. Timely blocking the transmission paths and isolating the infected and suspected patients are the gold principles for controlling and managing large and sudden infectious diseases (Zhang, Li, et al., 2020). Despite of China’s capability of responding to public health emergency has been progressively improved after experiencing infectious diseases such as Wenchuan earthquake, SARS, H7N9, gaps remain in the implementation of effective early warning system (Cao et al., 2020). For example, unexplained pneumonia cases was reported in hospital in Wuhan as early as December 2019. Unfortunately, the local government did not make appropriate judgments and efficiently respond to the early warning information reported by those medical professionals. In this context, considering the potential harm for the public caused by the infected and suspected cases, the medical professionals chose to announce the early warning information to a small portion of the population. They violated the public health ethics and said the truth about COVID-19 and relevantly penalized by the local government. Such reasons and facts led to the failure to effectively manage the COVID-19 in the early stage. The whistleblower’s ethical dilemma in medicine and public health and the behavior of whistleblowing is likely to influence strategic decisions about public health emergency (Cao et al., 2020; Kasambara et al., 2017; Kavanagh, 2020; Zhang, Li, et al., 2020; Zhu, 2020).

While existing research has found relations between government’s strategic decision, the early warnings, public’s attention (Banerjee & Meena, 2021; Cao et al., 2020; Gong et al., 2020; Hyland-Wood et al., 2021; Kavanagh, 2020; Tsao et al., 2021; Zhang, Chen, et al., 2020), research on combing with all the parties in pandemic early warning game has been found wanting. Although the government is the main party in this game system in the context of China, the current public health emergency preparedness should be improved through exploring the factors of strategic decisions
of three parties and interactive mechanism of the game system. Hence, the purpose of this study is to solve the whistleblower’s dilemma in a public health emergency. To deal with, this study attempts to apply the evolutionary game theory to construct a tripartite evolutionary game model composed of the local government, the whistleblower, and the public. Furthermore, this study will conduct the simulation analysis to explore the specific factors affecting the evolution of behavioral strategies among three parties under different conditions. By doing so, this study hopes to provide economic means and policy recommendations for implementing an effective early warning system for public health emergency.

The framework of this study is as follows. In Section 2, the information on China’s early warning system regarding public health emergency is introduced. We also briefly discuss the institutional barriers to, and multiple meanings of the whistleblower’s dilemma in that section. In Section 3, we construct a tripartite evolutionary game model including assumptions and a payoff matrix, and in Section 4, we conduct the stimulation analysis using MATLAB to illustrate the impact of factors on behavioral strategies among three parties under different cases. In Section 5, we draw conclusions and put forward corresponding suggestions of this study.

2 Literature Review

2.1 China’s Early Warning System

Public health emergencies such as SARS, H7N9, Ebola have occurred frequently in the past two decades. After experiencing the SARS outbreak in 2003, China established a multiple level system for prevention and control of public health emergencies(Cao et al., 2020). By doing this, China’s capability of the public health systems to respond to infectious diseases has been comprehensively improved. The vertical reporting of pandemic information in multiple level system ensures the accuracy and comprehensiveness of information and thus reduces social panic(Duan et al., 2021). However, this kind of mechanism would influence the timeliness of publishing
pandemic information to a certain extent, and is prone to distort and misjudge the early warning information during transmission (Lencucha & Bandara, 2021). As a result, it might cause remarkable deficiencies in pandemic prevention, controlling and management. From another perspective, the local government can help the public better understand the infectious disease through timely disclosing the information, reducing the social confusion and panic and promoting the public’s volunteering participation in preventing and controlling the disease. Therefore, timely disclosure of early warning information has a significant positive effect on the trust and satisfaction in government (Lencucha & Bandara, 2021; Liu et al., 2021). Thus, there is an inherent contradiction between the timeliness and accuracy of information disclosure, and the game equilibrium between the two becomes an important consideration for the local government to respond to the early warning information.

Given that a rapid development of self-media (i.e., independently operating social media accounts) in China accelerating the spread of public opinion on early warning information (Tsao et al., 2021), timely responding to the information is helpful to guide and shape the public opinion and reduce the infodemic\(^1\), as well as enhance the credibility of the local government and prevent to fall into the Tacitus trap\(^2\). Nevertheless, China’s public health policy requires the local government to make evidence based decisions. Thus the local government places the greater emphasis on the authenticity and reliability when disclosing early warning information (Cao et al., 2020; Zhang, Chen, et al., 2020). Under the framework of evidence based governance, managing public health emergencies is divided into three stages, namely, early warning period, controlling period, and reconstructing period. Among these, the core tasks of the early warning period are to scientifically evidence the risk information and then announce it to the public in a timely manner. The core tasks of medical professionals are to ensure that the early warning information can be delivered to decision makers

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\(^1\) A rapid and far-reaching spread of both accurate and inaccurate information about a pandemic.  
\(^2\) A credibility and legitimacy crisis of the government due to the loss of trust of the people.
and the public in a timely and accurate manner (Zhang, Chen, et al., 2020; Zhu et al., 2020). However, blocking and filtering of key evidence may occur during the vertical or upward transmission of information, which may affect the local government’s efficiency of administrative decision making and accuracy of judging early warning information.

2.2 The Whistleblower’s Dilemma

Due to the combined impacts of strategic decisions and information transmission mechanism, the whistleblower’s dilemma exists in managing public health emergencies. In particular, the contradiction between the timeliness and accuracy of information is the root cause of the whistleblower’s dilemma. Before exploring the whistleblower’s dilemma, it is necessary to understand the context in which the whistleblower lives in. Since existing laws and regulations in China lack clear rules and guidelines on the party and content of information disclosure, bring great challenges to China’s early warning system. Nevertheless, the relevant laws clearly specify the subjects of early warning system and their authority. That is, the subject of deciding and issuing an early warning information of a pandemic is limited to the national health administrative department, the provincial government and its health administrative department. The local governments, or institutions, or individuals below the provincial level do not have such authority (Cao et al., 2020; Zhu, 2020). Considering the evidence based principle of public policy in China, the administrative information disclosure is related to the social stability of a society, so the disclosure needs to be carefully considered by the government. Therefore, from an institutional perspective, one of the reasons that puts the whistleblower in a difficult position (i.e., dilemma) is that the institution of reporting early earning information to the government is overly complex and time-consuming (Cao et al., 2020; Duan et al., 2021). When a pandemic risk shows a sign of continuous spread, the higher authorities is still cautiously assessing or evaluating the risk information while the local government is waiting for higher authorities’ decisions (Zhang, Chen, et al., 2020; Zhang, Li, et al., 2020; Zhu et al., 2020). Therefore,
the absence of the distribution of the right and responsibility of the local government in public health emergency reflects the absence of the right to disclose information at the assessment stage. In fact, the institution of vertically reporting the risk information reflects more of a cautious attitude of the local government towards information disclosure. The rapid development of social media has made the public more sensitive to the risk information than in the past, the phenomenon such as infodemic is emerged, which undoubtedly amplifies the cautious response strategy adopted by the local government (Tsao et al., 2021).

As the key transmitter of information in public health emergency, the role of the whistleblower cannot be overlooked in public health emergency as this group can receive risk information in the first instance (Zhu, 2020). Hence in the early warning game system, the whistleblower has two kinds of strategic decision. One is to report the early warning information to the government and wait for the decisions to be announced, while the other is to announce the information and rise an alarm to the public or a small portion of population. However, given the need to maintain social stability, the voices of this group of people may be unable to affect the public’s perception of the potential risk of a pandemic (Powell, 2020, 2021). They may even be penalized by the local government for spreading ‘rumors’ or for breaking the regulations, leading to a situation where the spread of the pandemic is uncontrollable (Zhu, 2020). Thus, the local government is also challenged with two strategic decisions. One is to actively respond to the early warning information and prepare a contingency plan while the other is to cautiously respond to the early warning information but just wait for the decisions made by the upper authorities.

The strategies of multiple parties together constitute a profile in the early warning game system. Hence, the whistleblower’s dilemma takes two forms: one is the behavioral difference between the whistleblower and the public. For example, the whistleblower calls for the public to take preventive measures but are ignored by the public. The action of announcement may be even mistakenly perceived as disturbing
social order by the local government. The other is the discrepancy between the administrative information and the public opinion. For example, in the early stages of COVID-19 pandemic, a number of unidentified cases emerged one after another and the public opinion started to pay wide attention to this potential risk. The local government, on the other hand, chose to maintain social order and stability when it had not yet received a decision from the upper authorities, and failed to prepare a protective plan for the potential risk in time (Liu et al., 2021). Ultimately, the whistleblower announced the early warning information to the public with limited effect on the pandemic management (Zhang, Chen, et al., 2020; Zhu et al., 2020).

3 Methods

3.1 Participants and Strategic Decisions

The parties of the pandemic early warning system consist of the local government, the whistleblower, and the public. The whistleblower is a group of medical professionals who can grasp the risk information about a pandemic at the first time. The local government is the regional administrations that show signs of a pandemic, including governments below the provincial level and local health administrations in China (Zhou & Xin, 2021). In the game system, the whistleblower detects the suspected case and pandemic early warning information and reports to the local government and is subject to the observance of the law and regulations. However, the whistleblower may choose to announce the risk information to the public if stuck in a dilemma (Zhu, 2020). Therefore, the whistleblower's strategic decisions are {to announce the early warning information; not to announce the early warning information}.

After receiving the early warning information, the local government may timely and actively make appropriate evaluation and reports the risk information to the higher level authorities. But in the process of reporting information to higher authorities, local governments may face the multiple sources of information such as public opinions and opinions from expert panels. In order to make a prudent strategic decision, the
government may be cautious in responding to the information passed by the whistleblower. To avoid causing the social panic and fear, the local government may also punish the whistleblower for the information disclosure (Hyland-Wood et al., 2021; Kavanagh, 2020; Liu et al., 2021). Therefore, two strategic decisions for the local government to deal with the whistleblowing are \{active response strategy; cautious response strategy\} in the initial stage of a pandemic.

It is important to note that even if the local government chooses not to announce information about the pandemic in the initial stage, the potential risk may still attract public’s attention due to the increase of the suspected cases and the information disclosed by the whistleblower and public opinion on the internet (Banerjee & Meena, 2021). Public’s attention is an important factor in improving the efficiency of making informed decisions and responding quickly (Gong et al., 2020; Zhu et al., 2020). In order to maintain the stability of social order, public’s attention may put the local government in the position of having to announce the risk information. Thus in this case, the public’s strategic decisions are \{to pay attention to the early warning system ; not to pay any attention to the early warning system\}.

In summary, the local government’s active response strategies include paying full attention to the early warning information and timely preparing a contingency plan if deemed necessary. The probability of choosing the active response strategy by the local government is $x (0 \leq x \leq 1)$; The cautious response strategies include delaying the public announcement of warnings and punishing whistleblowers for information disclosure. Thus the probability of choosing the cautious response strategy by the government is $1 - x$. The whistleblower’s strategies include announcing the early warning information to the public or not. The probability of choosing to announce the early warning information to the public is noted as $y (0 \leq y \leq 1)$; The probability of choosing not to announce the early warning information to the public is noted as $1 - y$. The probability of the public staying informed is recorded as $z (0 \leq z \leq 1)$; The probability of the public choosing not to pay any attention to the early warning system
3.2 Basic Assumptions and Modelling

In order to analyze the strategic decisions among three parties, the following basic assumptions are set.

Assumption 1. In a pandemic early warning game model, the participants are the local government, the whistleblower, and the public. Each party is risk neutral bounded rationality subject to maximize their interests.

Assumption 2. The cost to the local government of choosing the active response strategy after receiving the early warning information is $\pi_1$. Accordingly, the cost of choosing the cautious response strategy is $\pi_2$; If the local government takes active response strategy and timely prepares an effective plan, then the credibility of the local government is enhanced by the public and which is denoted by $C_1$. On the contrary, the credibility of the local government is denoted by $C_2$.

Assumption 3. The cost to the whistleblower of choosing not to announce the early warning information to the public is $\pi_3$. On the contrary, the cost of choosing to announce the early warning information to the public is $\pi_4$. The additional income that the public can bring to the whistleblower is $Q$. If the whistleblower’s behaviour of hiding early warning information found out by the local government in the evolution of actively responding to a pandemic, then the local government imposes certain punishment of $P$ on the whistleblower.

Assumption 4. The cost for the public to pay attention to the early warning information delivered by the whistleblower is denoted by $\pi_5$. When the local government chooses the active response strategy, the behavior of staying informed is encouraged, and thus the public will receive the award of $R$ from the local government. Under the strategy of cautious response, if the whistleblower remains silent to the public while the public pays attention to early warning information, then the level of reputation obtained by the whistleblower is denoted by $R_1$. On the contrary, the level of reputation obtained by the whistleblower is denoted by $R_2$. The utility that the public can obtain
when they pay attention to the early warning information is denoted by $U_1$. On the contrary, the utility obtained by the public is denoted as $U_2$.

Based on the above discussions and assumptions, the local government, the whistleblower and the public constantly adjust their strategic decisions in the tripartite evolutionary game with finite rationality. The payoff matrix of the three parties under strategic interactions can be obtained, as shown in Tables 1.

**Table 1.** The payoff matrix of the local government, the whistleblower, and the public.

<table>
<thead>
<tr>
<th>The Whistleblower</th>
<th>The Public</th>
<th>The Local Government</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Active Response</td>
<td>Cautious Response Strategy ($x$)</td>
</tr>
<tr>
<td>Strategy of paying attention to the early warning system ($y$)</td>
<td>$P - \pi_1 - R + C_1$</td>
<td>$-\pi_2 + C_2$</td>
</tr>
<tr>
<td>Strategy of not paying any attention to the early warning system ($1 - y$)</td>
<td>$Q - P - \pi_4 + R_2$</td>
<td>$Q - \pi_4 + R_2$</td>
</tr>
<tr>
<td>Strategy of not announcing the early warning information ($1 - y$)</td>
<td>$U_2 - Q - \pi_5 + R$</td>
<td>$U_2 - Q - \pi_5$</td>
</tr>
<tr>
<td></td>
<td>Strategy of paying attention to the early warning system ($z$)</td>
<td></td>
</tr>
<tr>
<td>Strategy of announcing the early warning information ($z$)</td>
<td>$P - \pi_1$</td>
<td>$-\pi_2$</td>
</tr>
<tr>
<td>Strategy of paying attention to the early warning system ($z$)</td>
<td>$Q - P - \pi_4$</td>
<td>$Q - \pi_4$</td>
</tr>
<tr>
<td>Strategy of announcing the early warning information ($1 - z$)</td>
<td>$U_2 - Q$</td>
<td>$U_2 - Q$</td>
</tr>
<tr>
<td>Strategy of not announcing the early warning information ($1 - z$)</td>
<td>$-\pi_1 + C_1$</td>
<td>$-\pi_2 + C_2$</td>
</tr>
<tr>
<td>Strategy of paying attention to the early warning system ($1 - z$)</td>
<td>$Q - \pi_5 + R_1$</td>
<td>$Q - \pi_5 + R_1$</td>
</tr>
<tr>
<td>Strategy of announcing the early warning information ($1 - (1 - y)$)</td>
<td>$U_1 - Q - \pi_5$</td>
<td>$U_1 - Q - \pi_5$</td>
</tr>
</tbody>
</table>
3.3 Evolutionary Stability Analysis

3.3.1 The Local Government’s Evolutionary Stability Strategy

Based on the assumptions of this study, the probability of the local government choosing active response strategy is $x$, and the probability of choosing cautious response strategy is $(1 - x)$. $E_{11}$ and are $E_{12}$ used to represent the expected benefit of the local government chooses active response strategy and cautious response strategy, respectively, and $\bar{E_1}$ represents the overall expected benefit of the local government.

The expected benefit of the active response strategy selected by the local government are:

$$E_{11} = yz(P - \pi_1 - R + C_1) + (1 - y)z(-\pi_1 + C_1) + y(1 - z)(P - \pi_1) + (1 - y)(1 - z)(-\pi_1)$$  \hspace{1cm} (1)

The expected benefit of the cautious response strategy selected by the local government are:

$$E_{12} = yz(-\pi_2 + C_2) + (1 - y)z(-\pi_2 + C_2) + y(1 - z)(-\pi_2) + (1 - y)(1 - z)(-\pi_2)$$  \hspace{1cm} (2)

According to Equations (1) and (2), the overall expected benefit of the two government’s strategic decisions are:

$$\bar{E_1} = xE_{11} + (1 - x)E_{12}$$  \hspace{1cm} (3)

According to Equation (3), the replicator dynamics equation of the local government can be calculated as:
\[ F(x) = x(1-x)(E_{11} - E_{12}) = x(1-x)(yP + z(C_1 - C_2) - yzR - (\pi_1 - \pi_2)) \] (4)

To further analyze the impact of the size of the local government with different decisions on the stable equilibrium of the strategic evolution, we can obtain the derivative of the replicator dynamics equation with respect to \( x \):

\[ \frac{dF(x)}{dx} = (1 - 2x)(yP + z(C_1 - C_2) - yzR - (\pi_1 - \pi_2)) \] (5)

Thus for the local government, we can make the following summary according to the above equation.

1. When \( y = y^* = \frac{(\pi_1 - \pi_2) - z(C_1 - C_2)}{p - zR} \), \( F(x) \equiv 0 \), in this case, any proportion \( x \) that the local government chooses randomly is an evolutionary stable strategy.

2. When \( 0 < y < y^* = \frac{(\pi_1 - \pi_2) - z(C_1 - C_2)}{p - zR} \), \( F(0) = 0 \), \( F(1) = 0 \), \( F'(0) < 0 \), and \( F'(1) > 0 \), the evolutionary stability strategy of the local government is \( x^* = 0 \). In this case, when the proportion of the whistleblower that chooses the strategy of announcing the early warning information is lower than \( \frac{(\pi_1 - \pi_2) - z(C_1 - C_2)}{p - zR} \), the local government tends to choose the cautious response strategy. Because the active response strategy may result in a greater cost.

3. When \( \frac{(\pi_1 - \pi_2) - z(C_1 - C_2)}{p - zR} = y^* < y < 1 \), \( F(0) = 0 \), \( F(1) = 0 \), \( F'(0) > 0 \), \( F'(1) < 0 \), the evolutionary stable strategy of the government group is \( x^* = 1 \). In this case, when the proportion of the whistleblower that chooses the strategy of announcing the early warning information is higher than \( \frac{(\pi_1 - \pi_2) - z(C_1 - C_2)}{p - zR} \), the local government tends to choose the active response strategy. The reason is the higher proportion of the whistleblowing may affect the standard prevention and control methods, so the local government shall choose the certain active response strategy to ensure the normal development of society.

Based on the above analysis, we can draw a dynamic replication phase diagram of the local government, as shown in Figure 1.
3.3.2 The Whistleblower’s Evolutionary Stability Strategy

Based on the assumptions of this study, the probability of the whistleblower choosing to announce the early warning information is \( y \), and the probability of choosing not to announce the early warning information is \((1 - y)\). \( E_{21} \) and \( E_{22} \) are used to represent the expected benefit of the whistleblower chooses the strategies of announcing or not announcing the early warning information, and \( E_2 \) represents the overall expected benefit of the whistleblower.

The expected benefit when the whistleblower chooses to announce the early warning information are:

\[
E_{21} = xz(Q - P - \pi_4 + R_2) + (1 - x)z(Q - \pi_4 + R_2) + x(1 - z)(Q - P - \pi_4) + (1 - x)(1 - z)(Q - \pi_4)
\]  
\[\text{(6)}\]

The expected benefit when the whistleblower chooses not to announce the early warning information are:

\[
E_{22} = xz(Q - \pi_3 + R_1) + (1 - x)z(Q - \pi_3 + R_1) + x(1 - z)(Q - \pi_3) + (1 - x)(1 - z)(Q - \pi_3)
\]  
\[\text{(7)}\]

According to Equations (6) and (7), the overall expected benefit of the two whistleblower’s strategic decisions are:

\[
E_2 = yE_{21} + (1 - y)E_{22}
\]
\[
= y(xz(Q - P - \pi_4 + R_2) + (1 - x)z(Q - \pi_4 + R_2) + x(1 - z)(Q - P - \pi_4) + (1 - x)(1 - z)(Q - \pi_4)) + (1 - y)(xz(Q - \pi_3 + R_1) + (1 - x)z(Q - \pi_3 + R_1) + x(1 - z)(Q - \pi_3) + (1 - x)(1 - z)(Q - \pi_3))
\]  
\[\text{(8)}\]

According to Equation (8), the replicator dynamics equation of the whistleblower can be calculated as:
\[ F(y) = y(1 - y)(z(R_2 - R_1) - Px + (\pi_3 - \pi_4)) \]  

(9)

To further analyze the impact of the size of the whistleblower with different decisions on the stable equilibrium of the strategic evolution, we can obtain the derivative of the replicator dynamics equation with respect to \( y \) as follows:

\[ \frac{dF(y)}{dy} = (1 - 2y)(z(R_2 - R_1) - Px + (\pi_3 - \pi_4)) \]  

(10)

Thus for the whistleblower, we can make the following summary according to the above equation.

1. When \( x^* = \frac{z(R_2 - R_1) + (\pi_3 - \pi_4)}{p} \), \( F(y) \equiv 0 \), in this case, any proportion \( y \) that the whistleblower chooses randomly is an evolutionary stable strategy.

2. When \( 0 < x < x^* = \frac{z(R_2 - R_1) + (\pi_3 - \pi_4)}{p} \), \( F(0) = 0 \), \( F(1) = 0 \), \( F'(0) > 0 \), and \( F'(1) < 0 \), the evolutionary stability strategy of the whistleblower is \( y^* = 1 \). In this case, when the proportion of the local government that chooses the active response strategy is lower than \( \frac{z(R_2 - R_1) + (\pi_3 - \pi_4)}{p} \), the whistleblower tends to choose not to announce the early warning information. Because there may be a greater cost for the whistleblower choosing to announce the information.

3. When \( x^* = \frac{z(R_2 - R_1) + (\pi_3 - \pi_4)}{p} < x < 1 \), \( F(0) = 0,F(1) = 0,F'(0) < 0,F'(1) > 0 \), the evolutionary stable strategy of the whistleblower is \( y^* = 0 \). In this case, when the proportion of the local government that chooses the active response strategy is higher than \( \frac{z(R_2 - R_1) + (\pi_3 - \pi_4)}{p} \), the whistleblower tends to choose to announce the early warning information.

Based on the above analysis, we can draw a dynamic replication phase diagram of the local government, as shown in Figure 2.
strategic decisions.

3.3.3 The Public’s Evolutionary Stability Strategy

Based on the assumptions of this study, the probability of the public choosing to pay attention to the early warning system is \( z \), and the probability of choosing not to pay any attention to the early warning system is \( 1 - z \). \( E_{31} \) and \( E_{32} \) are used to represent the expected benefit of the public chooses the strategies of paying or not paying any attention to the early warning system, and \( E_3 \) represents the overall expected benefit of the public.

The expected benefit when the public chooses to pay attention to the early warning system are:

\[
E_{31} = xy(U_2 - Q - \pi_5 + R) + x(1 - y)(U_1 - Q - \pi_5) + (1 - x)y(U_2 - Q - \pi_5) + (1 - x)(1 - y)(U_1 - Q - \pi_5)
\]  

(11)

The expected benefit when the public chooses not to pay any attention to the early warning system are:

\[
E_{32} = xy(U_2 - Q) + x(1 - y)(U_1 - Q) + (1 - x)y(U_2 - Q) + (1 - x)(1 - y)(U_1 - Q)
\]  

(12)

According to Equations (11) and (12), the overall expected benefit of the two whistleblower’s strategic decisions are:

\[
E_3 = zE_{31} + (1 - z)E_{32} = z(xy(U_2 - Q - \pi_5 + R) + x(1 - y)(U_1 - Q - \pi_5) + (1 - x)y(U_2 - Q - \pi_5) + (1 - x)(1 - y)(U_1 - Q - \pi_5)) + (1 - z)(xy(U_2 - Q) + x(1 - y)(U_1 - Q) + (1 - x)y(U_2 - Q) + (1 - x)(1 - y)(U_1 - Q))
\]  

(13)

According to Equation (13), the replicator dynamics equation of the public can be calculated as:

\[
F(z) = z(1 - z)(xyR - \pi_5)
\]  

(14)

To further analyze the impact of the size of the public with different decisions on the stable equilibrium of the strategic evolution, we can obtain the derivative of the replicator dynamics equation with respect to \( z \) as follows:

\[
\frac{dF(z)}{dz} = (1 - 2z)(xyR - \pi_5)
\]  

(15)
Thus for the public, we can make the following summary according to the above equation.

1. When \( y = y^* = \frac{\pi_s}{xR} \), \( F(z) \equiv 0 \), in this case, any proportion \( z \) that the public chooses randomly is an evolutionary stable strategy.

2. When \( 0 < y < y^* = \frac{\pi_s}{xR} \), \( F(0) = 0, F(1) = 0, F'(0) < 0, F'(1) > 0 \), the evolutionary stability strategy of the public is \( z^* = 0 \). In this case, when the proportion of the whistleblower that chooses to announce the early warning information is lower than \( \frac{\pi_s}{xR} \), the public tends to choose not to pay any attention to the early warning system. At this stage, the less information is made publicly available, thus leaving the public less informed and therefore inclined to believe that the level of risk is low.

3. When \( \frac{\pi_s}{xR} = y^* < y < 1 \), \( F(0) = 0, F(1) = 0, F'(0) > 0, F'(1) < 0 \), the evolutionary stable strategy of the public is \( z^* = 1 \). In this case, when the proportion of the whistleblower that chooses the strategy of announcing the early warning information is higher than \( y = y^* = \frac{\pi_s}{xR} \), the public tends to choose to pay the attention to the early warning system.

Based on the above analysis, we can draw a dynamic replication phase diagram of the local government, as shown in Figure 3.

**Figure 3.** Dynamic replication phase diagram of the evolution of the public’s strategic decisions.

### 3.3.4 Stability Analysis of Mix-Strategy Equilibrium

To explore the mutual interaction among the local government, the whistleblower, and
the public, we integrate above three replicator dynamic equations into a three-dimensional replicator dynamic game system of pandemic early warning system:

\[
\begin{align*}
F(x) &= x(1 - x)(yP + z(C_1 - C_2) - yzR - (\pi_1 - \pi_2)) \\
F(y) &= y(1 - y)(z(R_2 - R_1) - Px + (\pi_3 - \pi_4)) \\
F(z) &= z(1 - z)(xyR - \pi_5)
\end{align*}
\]  

(16)

Let \( F(x) = 0 \), \( F(y) = 0 \), and \( F(z) = 0 \), concurrently, we can get nine equilibrium points of system (16). They are \( E_1 (0, 0, 0) \), \( E_2 (0, 1, 0) \), \( E_3 (0, 0, 1) \), \( E_4 (0, 1, 1) \), \( E_5 (1, 0, 0) \), \( E_6 (1, 0, 1) \), \( E_7 (1, 1, 0) \), \( E_8 (1, 1, 1) \), and \( E_9 (x^*, y^*, z^*) \). Evidently, \( E_1 \) to \( E_8 \) are pure Nash equilibria, while point \( E_9 \) is a mixed Nash equilibrium. For the reason that any strict Nash equilibrium must be a pure strategy, it is enough to discuss the stability of equilibrium solutions \( E_1 \) to \( E_8 \), and \( E_9 \) cannot be stable.

Hence, the stability of each equilibrium solution is analyzed through leveraging the Jacobian matrix of the above three-dimensional replicator dynamic game system (Equation 15):

\[
J = \begin{bmatrix}
\frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} & \frac{\partial F(x)}{\partial z} \\
\frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} & \frac{\partial F(y)}{\partial z} \\
\frac{\partial F(z)}{\partial x} & \frac{\partial F(z)}{\partial y} & \frac{\partial F(z)}{\partial z}
\end{bmatrix}
\]  

(17)

The eigenvalues of the Jacobian matrix at eight equilibrium points are shown in Table 2.

<table>
<thead>
<tr>
<th>Equilibrium points</th>
<th>( \lambda_1 )</th>
<th>( \lambda_2 )</th>
<th>( \lambda_3 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E_1 (0, 0, 0) )</td>
<td>(- (\pi_1 - \pi_2))</td>
<td>((\pi_3 - \pi_4))</td>
<td>(-\pi_5)</td>
</tr>
<tr>
<td>( E_2 (0, 0, 1) )</td>
<td>((C_1 - C_2) - (\pi_1 - \pi_2))</td>
<td>((R_2 - R_1) + (\pi_3 - \pi_4))</td>
<td>(\pi_5)</td>
</tr>
<tr>
<td>( E_3 (0, 1, 0) )</td>
<td>(P - (\pi_1 - \pi_2))</td>
<td>(- (\pi_3 - \pi_4))</td>
<td>(-\pi_5)</td>
</tr>
</tbody>
</table>
If the local government adopts the active response strategy, such as organizing medical professionals to carry out timely research and evaluation, and improving the efficiency of information publication, which will bring a positive effect on the credibility of the local government (Hyland-Wood et al., 2021). While the local government chooses the cautious strategy, such as relaxing the vigilance or not paying full attention to early warning information, which will bring a negative impact on the credibility of the local government and seriously hinder the management of the pandemics (Hyland-Wood et al., 2021; Lencucha & Bandara, 2021). At the same time, the whistleblower, as the first party with access to information about a potential risk, will have a high reputation for timely early warnings. Therefore, taking into account real-life scenarios, \( C_1 > C_2 \) and \( \pi_5 > 0 \) are satisfied. During the early days of the pandemic, the strategic decisions made by the whistleblower have a profound impact on the local government's risk management. Firstly, considering the accuracy of the information, if the initial assessment is that the early warning information is wrong, the whistleblowing may lead to an information pandemic on the internet, and thus social panic (Duan et al., 2021; Tsao et al., 2021). Consequently, the local government is more inclined to choose the cautious response strategy.

Hence, in the replicator dynamic game system of the local government, the
whistleblower and the public, the behavioral strategies of the three parties are influenced by multiple factors. Thus we begin by looking at the local government’s strategic decisions, and constructing game paths for early warning system under the conditions of $\pi_1 - \pi_2 < 0$ and $\pi_1 - \pi_2 > 0$.

Case 1: When the conditions of $\pi_1 - \pi_2 < 0$, $C_1 > C_2$, and $\pi_5 > 0$ are all satisfied, $E_4(1, 0, 0)$, $E_5(1, 1, 0)$, and $E_8(1, 1, 1)$ are the potential evolutionary stable strategies. From the condition of , we can observe that the cost to the government of choosing cautious response strategy is much greater than the cost of choosing active response strategy. At the same time, there is the outbreak risk of pandemics. The stability of the equilibrium points in Case 1 is shown in Table 3.

![Table 3. Stability of the equilibrium points in Case 1.](image)

<table>
<thead>
<tr>
<th>Equilibrium points</th>
<th>$\lambda_1$</th>
<th>$\lambda_2$</th>
<th>$\lambda_3$</th>
<th>Stability</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_1(0, 0, 0)$</td>
<td>$&gt;0$</td>
<td>---</td>
<td>$&lt;0$</td>
<td>Unstable</td>
<td>N/A</td>
</tr>
<tr>
<td>$E_2(0, 0, 1)$</td>
<td>---</td>
<td>---</td>
<td>$&gt;0$</td>
<td>Unstable</td>
<td>N/A</td>
</tr>
<tr>
<td>$E_3(0, 1, 0)$</td>
<td>$&gt;0$</td>
<td>---</td>
<td>$&lt;0$</td>
<td>Unstable</td>
<td>N/A</td>
</tr>
<tr>
<td>$E_4(1, 0, 0)$</td>
<td>$&lt;0$</td>
<td>---</td>
<td>$&lt;0$</td>
<td>To be discussed</td>
<td>$(\pi_3 - \pi_4) &lt; P$</td>
</tr>
<tr>
<td>$E_5(1, 1, 0)$</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>To be discussed</td>
<td>$R &lt; \pi_5$, $P - (\pi_3 - \pi_4) &lt; 0$</td>
</tr>
<tr>
<td>$E_6(1, 0, 1)$</td>
<td>---</td>
<td>---</td>
<td>$&gt;0$</td>
<td>Unstable</td>
<td>N/A</td>
</tr>
<tr>
<td>$E_7(0, 1, 1)$</td>
<td>$&lt;0$</td>
<td>---</td>
<td>$&gt;0$</td>
<td>Unstable</td>
<td>N/A</td>
</tr>
<tr>
<td>$E_8(1, 1, 1)$</td>
<td>$&lt;0$</td>
<td>---</td>
<td>---</td>
<td>To be discussed</td>
<td>$R &gt; \pi_5$, $(R_2 - R_1) + (\pi_3 - \pi_4) &gt; P$</td>
</tr>
</tbody>
</table>

To be specific, when the conditions of $\pi_1 - \pi_2 > 0$ and $(\pi_3 - \pi_4) < P$ are all satisfied, $E_4(1, 0, 0)$ is the only one evolutionary stable strategy. That is, the local
government chooses the cautious response strategy when the cost of cautious response strategy is lower than the cost of active response strategy. The whistleblower chooses the strategy of not announcing the early warning information when the cost of announcement is relatively higher. Concurrently, the public may choose not to pay any attention to the early warning system. When the conditions of \( \pi_1 - \pi_2 < 0, R < \pi_5, P - (\pi_3 - \pi_4) < 0 \) are all satisfied, \( E_5 \) (1, 1, 0) is the only one evolutionary stable strategy. That is, the local government chooses the active response strategy when the cost of active response strategy is relatively lower. The whistleblower chooses the strategy of announcing the early warning information when the cost of the announcement is relatively lower as well. Because the public has limited access to information, the public will stabilize on a strategy of not paying any attention to the early warning system when it maintains an optimistic judgment about the country's public health emergency preparedness (i.e., \( R < \pi_5 \)). When the conditions of \( \pi_1 - \pi_2 < 0, R > \pi_5, (R_2 - R_1) + (\pi_3 - \pi_4) > P \) are all satisfied, \( E_8 \) (1, 1, 1) is the only one evolutionary stable strategy. That is, the local government chooses the active response strategy while the whistleblower tends to choose the strategy of announcing the early warning information because of its lower cost. In this regard, the public chooses the strategy of paying attention to the early warning system because it might be helpful in saving the lives and property(Zhu et al., 2020). In other words, if all three parties adopt a proactive strategy to reduce the potential losses, the game system of pandemic early warning will reach an optimal equilibrium.

There is an alternative hypothesis: the cost of the local government's active response strategy is relatively higher. This means that the early warning information is of questionable accuracy (i.e., \( \pi_1 - \pi_2 > 0 \)). In other words, there is an infodemic risk in this case. As facts, rumors, and fears get together and disperse, it becomes difficult for the public to find trustworthy sources and guidance, thus affecting the public’s judgment and health(Banerjee & Meena, 2021).

Case 2: When the condition of is satisfied, the cost to the government of choosing
cautious response strategy is lower than the cost of choosing active response strategy.

The stability of the equilibrium points in Case 2 is shown in Table 4.

Table 4. Stability of the equilibrium points in Case 2.

<table>
<thead>
<tr>
<th>Equilibrium points</th>
<th>$\lambda_1$</th>
<th>$\lambda_2$</th>
<th>$\lambda_3$</th>
<th>Stability</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>E₁ (0, 0, 0)</td>
<td>&lt;0</td>
<td>—</td>
<td>&lt;0</td>
<td>To be discussed</td>
<td>$\pi_3 - \pi_4 &lt; 0$</td>
</tr>
<tr>
<td>E₂ (0, 0, 1)</td>
<td>—</td>
<td>—</td>
<td>&gt;0</td>
<td>Unstable</td>
<td>N/A</td>
</tr>
<tr>
<td>E₃ (0, 1, 0)</td>
<td>—</td>
<td>—</td>
<td>&lt;0</td>
<td>To be discussed</td>
<td>$p - (\pi_1 - \pi_2) &lt; 0, \pi_3 - \pi_4 &gt; 0$</td>
</tr>
<tr>
<td>E₄ (1, 0, 0)</td>
<td>&gt;0</td>
<td>—</td>
<td>&lt;0</td>
<td>Unstable</td>
<td>N/A</td>
</tr>
<tr>
<td>E₅ (1, 1, 0)</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>To be discussed</td>
<td>$p - (\pi_1 - \pi_2) &gt; 0, P - (\pi_3 - \pi_4) &lt; 0, R &lt; \pi_5$</td>
</tr>
<tr>
<td>E₆ (1, 0, 1)</td>
<td>—</td>
<td>—</td>
<td>&gt;0</td>
<td>Unstable</td>
<td>N/A</td>
</tr>
<tr>
<td>E₇ (0, 1, 1)</td>
<td>—</td>
<td>&gt;0</td>
<td>—</td>
<td>Unstable</td>
<td>N/A</td>
</tr>
<tr>
<td>E₈ (1, 1, 1)</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>To be discussed</td>
<td>$R &gt; \pi_5, P + (C_1 - C_2) - (\pi_1 - \pi_2) &gt; 0, (R_2 - R_1) - P + (\pi_3 - \pi_4) &gt; 0$</td>
</tr>
</tbody>
</table>

To be specific, when conditions of $\pi_1 - \pi_2 > 0$ and $\pi_3 - \pi_4 < 0$ are all satisfied, E₁ (0, 0, 0) is the only one evolutionary stable strategy. That is, the local government chooses the cautious response strategy when the cost of cautious response strategy is lower than the cost of active response strategy. The whistleblower chooses the strategy of not announcing the early warning information when the cost of announcement is relatively higher. Concurrently, the public may choose not to pay any attention to the early warning system. When the conditions of $\pi_1 - \pi_2 > 0, p - (\pi_1 - \pi_2) < 0, \pi_3 - \pi_4 > 0$ are all satisfied, E₃ (0, 1, 0) is the only one evolutionary stable strategy.
strategy. That is, the local government chooses the active response strategy when the cost of active response strategy is relatively lower. The whistleblower chooses the strategy of announcing the early warning information when the cost of the announcement is relatively lower as well. In this context, the public will stabilize on a strategy of not paying any attention to the early warning system as official information is not yet released. When the conditions of $\pi_1 - \pi_2 > 0, p - (\pi_1 - \pi_2) > 0, P - (\pi_3 - \pi_4) < 0, R < \pi_5$ are all satisfied, $E_5(1, 1, 0)$ is the only one evolutionary stable strategy. That is, when the penalty of keeping silent (i.e., not announcing the early warning information) is higher than the response cost while the penalty of keeping silent is also lower than the cost of announcement, the local government will choose the active response strategy and the whistleblower will stabilize on the strategy of announcing the early warning information. Concurrently, the public will stabilize on a strategy of not paying any attention to the early warning system (i.e., $R < \pi_5$). When $\pi_1 - \pi_2 > 0, R > \pi_5, (R_2 - R_1) - P + (\pi_3 - \pi_4) > 0, P + (C_1 - C_2) - (\pi_1 - \pi_2) > 0$ are all satisfied, $E_8(1, 1, 1)$ is the only one evolutionary stable strategy. This means that when the behavior of whistleblowing is more meaningful and influential than keeping silent, the whistleblower tends to announce the early warning information, while the local government steadily chooses the active response strategy, and the public is more inclined to choose the strategy of paying attention to the early warning system (Powell, 2020; Zhu, 2020). In such situation, the game system of pandemic early warning will reach an optimal equilibrium.

4 Simulation Analysis

By using MATLAB, we simulate the tripartite evolutionary game model under different conditions.

Case 1.1: The parameters ($\pi_1 = 5, \pi_2 = 10, \pi_3 = 4, \pi_4 = 6$) are set when the cost of the active response strategy is relatively lower and the cost of early warning announcement is relatively higher. Accordingly, the strategy for the stable state in this
case is that the local government actively responds to the pandemic early warning information, the whistleblower remains silent to the public, and the public does not pay any attention to the early warning system. The dynamic evolution path of Case 1.1 is shown in Figure 4.

![Figure 4](image.png)

**Figure 4.** Dynamic evolution path of Case 1.1.

Case 1.2: The parameters ($\pi_1 = 5$, $\pi_2 = 10$, $\pi_3 = 10$, $\pi_4 = 4$, $\pi_5 = 5$, $P = 4$, $R = 3$) are set when the public’s attention is relatively lower, the cost of the active response strategy is relatively lower, and the cost of keeping silent is relatively higher. Accordingly, the strategy for the stable state in this case is that the local government actively responds to the pandemic early warning information, the whistleblower announces the early warning information, but the public does not pay any attention to the early warning system. The dynamic evolution path of Case 1.2 is shown in Figure 5.
Case 1.3: The parameters ($\pi_1 = 5$, $\pi_2 = 10$, $\pi_3 = 12$, $\pi_4 = 5$, $\pi_5 = 3$, $P = 4$, $R = 3$, $R_1 = 8$, $R_2 = 6$) are set when the benefit of attention is relatively higher, the cost of the active response strategy is relatively lower, and the cost of announcement is relatively lower. Accordingly, the strategy for the stable state in this case is that the local government actively responds to the pandemic early warning information, the whistleblower announces the early warning information, and the public also pays full attention to the early warning system. The dynamic evolution path of Case 1.3 is shown in Figure 6.
Case 2.1: The parameters \( \pi_1 = 10, \pi_2 = 5, \pi_3 = 6 \) are set when the cost of the cautious response strategy is relatively lower, but the cost of announcement is relatively higher. Accordingly, the strategy for the stable state in this case is that the local government cautiously responds to the pandemic early warning information and the whistleblower does not announce the early warning information, while the public does not pay attention to the early warning system. The dynamic evolution path of Case 2.1 is shown in Figure 7.

Case 2.2: The parameters \( \pi_1 = 10, \pi_2 = 5, \pi_3 = 9, \pi_4 = 6, P = 4 \) are set when the cost of the cautious response strategy is relatively lower, but the cost of keeping silent is relatively higher. Accordingly, the strategy for the stable state in this case is that the local government cautiously responds to the pandemic early warning information and the whistleblower announces the early warning information, while the public does not pay attention to the early warning system. The dynamic evolution path of Case 2.2 is shown in Figure 8.
Case 2.3: The parameters \((\pi_1 = 6, \pi_2 = 5, \pi_3 = 9, \pi_4 = 4, \pi_5 = 5, P = 4)\) are set when the public’s attention is relatively lower, the cost of keeping silent is much higher than the response cost while the penalty of keeping silent is lower than the cost of announcement. Accordingly, the strategy for the stable state in this case is that the local government actively responds to the pandemic early warning information, the whistleblower announces the early warning information, but the public does not pay any attention to the early warning system. The dynamic evolution path of Case 2.3 is shown in Figure 9.
Case 2.4: The parameters (\(\pi_1 = 6\), \(\pi_2 = 5\), \(\pi_3 = 9\), \(\pi_4 = 4\), \(\pi_5 = 2\), \(P = 4\), \(C_1 = 4\), \(C_2 = 2\), \(R_1 = 6\), \(R_2 = 9\), \(R = 3\)) are set when the behavior of whistleblowing is more meaningful and influential than keeping silent and the benefit of attention is relatively higher. Accordingly, the strategy for the stable state in this case is that the local government actively responds to the pandemic early warning information, the whistleblower announces the early warning information, and the public pays full attention to the early warning system. The dynamic evolution path of Case 2.4 is shown in Figure 10.
5 Discussion and Conclusion

With the continuous improvement of China's emergency management system, the capability of addressing the public health emergencies has been significantly enhanced. However, there are still numerous challenges in the pandemic early warning system, and a tripartite evolutionary game model composed of the local government, the whistleblower and the public was emerged in the current study. We also explored the stability of the game model by analyzing the strategic decisions of three parties. By using MATLAB, we then stimulated the stable state of strategies in different cases.

The findings of numerical analysis suggest that the whistleblower's dilemma in the context of a pandemic is essentially related to the inadequacy of the current early warning system. The cost of announcing the early warning information for the whistleblower, the cost of responding to early warning information for the local government and the benefit of paying attention significantly influence the behavioral strategies among the three parties. When there is a serious pandemic risk, the local governments tends to adopt an active response strategy in the first instance to reduce possible loss of life and property. When the accuracy of the received early warning information is questionable or hard to judge, the local government tends to adopt a cautious response strategy to reduce the potential loss to the society. In this regard, the whistleblower chooses to cross the rules and public health ethics to announce the early warning information due to the increased risk of significant harm for the public. As a group with limited access to information, the public's strategic decisions are significantly influenced by the decisions of the local government and the whistleblower. As a result, the whistleblower is potentially faced with a dilemma in the early warning game system. All three parties are likely to simultaneously choose proactive strategies when the effectiveness of the whistleblowing is higher than the penalty of keeping silent, and the benefit of attention is higher for the public.
Accordingly, our findings reveal the importance of the whistleblowing in the early warning game system. It also stresses that an effective early warning system for public health emergency is essentially a stable state of strategies reached by the local government, the whistleblower, and the public. The originality of the current study lies in the inclusion of the whistleblowing in exploring China's pandemic early warning system. Since this study concerns three parties’ behavioral strategies, providing a new research direction and enhancing the effectiveness of early warning system by analyzing the tripartite dynamic interactions.

Our findings also provide support for policy recommendations for promoting public health emergency preparedness. Firstly, the government is required to strengthen the pandemic early warning system. Timely response to the whistleblower's early warning information is crucial to controlling the spread of a pandemic (Zhang, Li, et al., 2020). The cost of the whistleblowing and the local government’s judgement of the response cost are two important factors affecting the pandemic early warning system. The cost of early warning can also be reduced by implementing a protection policy for the whistleblower. In addition to this, the whistleblowing can be incorporated into the social credit assessment mechanism. In addition to this, the whistleblowing can also be incorporated into the social credit assessment mechanism, and the emergence of infodemic can be reduced through effective constraints and supervision. Secondly, the assessment of the local government’s risk management should be improved. At present, the government's management systems lack the dimension of assessing the capacity to prevent and control risks (Cao et al., 2020; Kasambara et al., 2017). This may indirectly cause the spread of pandemics and ultimately put the public in a passive position in health emergencies.

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