Journal of Financial Economics 135 (2020) 1–15

Contents lists available at ScienceDirect

Journal of Financial Economics

journal homepage: www.elsevier.com/locate/jfec

Dynamic interventions and informational linkages[☆]

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ARTICLE INFO

Article history:
Received 13 June 2017
Revised 27 November 2017
Accepted 12 February 2018
Available online 15 May 2019

JEL classification:
D83
G01
G28

Keywords:
Coordination failures
Government intervention
Information design
Financial crisis
Global games
Learning

ABSTRACT

We model a dynamic economy with strategic complementarity among investors and study how endogenous government interventions mitigate coordination failures. We establish equilibrium existence and uniqueness, and we show that one intervention can affect another through altering the public information structure. A stronger initial intervention helps subsequent interventions through increasing the likelihood of positive news, but also leads to negative conditional updates. Our results suggest optimal policy should emphasize initial interventions when coordination outcomes tend to correlate. Neglecting informational externalities of initial interventions results in over- or under-interventions. Moreover, saving smaller funds disproportionally more can generate greater informational benefits at smaller costs.

1. Introduction

Coordination failures are prevalent and socially costly. Effective interventions can ameliorate such damaging outcomes. For example, financial systems, especially short-term credit markets, are vulnerable to runs by investors. The 2007–2009 financial crisis witnessed a series of runs on both financial and nonfinancial institutions. In response, governments and central banks around the globe employed an array of policy actions. Given the novelty, the scale, the cost, and the intertwined nature of such interventions, a study of how endogenous interventions relate to each other is natural.

More broadly, how should a government formulate intervention policy in a dynamic economy with strategic complementarity? How does intervention in one institution or market affect subsequent interventions in other institutions or markets? This paper tackles these questions by modeling the government as a large player

☆ The paper was previously titled “Intervention policy in a dynamic environment: Coordination and learning.” We would like to thank two anonymous referees, the editor, Douglas Diamond, Alex Frankel, Pingyang Gao, Itay Goldstein, Zhiguo He, Anil Kashyap, Stephen Morris, Kyoungwon Seo, Xavier Vives, Yao Zeng, Pavel Zryumov, and seminar participants at University of Chicago Booth School of Business, Cheung Kong Graduate School of Business, École Polytechnique Fédérale de Lausanne, Peking University Guanghua School of Management, HEC Lausanne, Swiss Finance Institute, Shanghai University of Finance and Economics, University of Southern California Marshall School of Business, Finance Theory Group Meeting, American Finance Association Meeting, Wharton Liquidity Conference, Asian Finance Association Meeting, Auckland Finance Conference, and the Econometric Society Asian Meeting for helpful comments and discussions. This research was funded in part by the Fama-Miller Center for Research in Finance at the University of Chicago Booth School of Business. All remaining errors are ours.

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https://doi.org/10.1016/j.jfineco.2019.05.011

in sequential global games and focusing on information transmission from one intervention to another. We reach three findings. First, an intervention not only improves welfare contemporaneously, but also affects agents' future coordination game and thus future interventions. Consequently, when intervention costs are comparable across coordination games, optimal policy often features an emphasis on the initial intervention. Second, decision makers for one intervention may not internalize the informational externality of the intervention outcome on other interventions and, thus, may over- or under-intervene, depending on the intervention costs. Third, an optimal policy may entail saving smaller funds disproportionally more. Such a policy generates an information structure with lower cost but greater benefits. The insights apply to situations with multiple interventions in which agents' actions exhibit strategic complementarity. Examples include interventions in currency attacks, bank runs, real estate programs, cross-sector industrialization, and technology subsidy programs.

We introduce the model in the context of runs in September 2008 on money market mutual funds (MMMFs) and subsequently on commercial papers, both triggered by investors' interpretation of Lehman Brothers' failure as a revelation of the credit risk and systemic illiquidity of commercial papers. The initial successful intervention with insurance to all MMMF depositors and the Asset-Backed Commercial Paper Money Market Mutual Fund Liquidity Facility (AMLF) arguably affected how investors reacted to later interventions in the commercial paper market, such as the Commercial Paper Funding Facility (CPFF) program.[1] Another context that motivates the study is the federal government's multiple attempts at stabilizing the housing market in a wide range of regions through the Neighborhood Stabilization Programs (NSPs) of 2008–2010 (Westrupp, 2017). These interventions provided funding for local housing authorities to purchase, renovate, and sell foreclosed properties in an effort to moderate the sizable declines in home prices driven by the massive wave of foreclosures during the credit crisis.[2] Because the intervention outcomes were revealed gradually over time, and housing markets across neighborhoods share common components, people update their priors on the underlying health of housing markets from initial intervention outcomes and behave differently in the local program.

Specifically, in a two-period economy, a group of atomistic investors in each period choose whether to run or remain invested in a fund. Running guarantees a certain payoff, which is higher than that of staying if the fund fails, whereas staying pays more if the fund survives. The fund survives if and only if the total measure of investors who choose to stay is above a fundamental threshold θ, interpreted as an unhedgeable system-wide illiquidity shock or the persistent quality of the underlying investment, and is identical across the two periods. Following the global games framework, θ in each period is unobservable and each investor receives a noisy signal. Prior literature has established that, in static settings, a unique equilibrium exists in which the fund survives as long as the true θ is below a threshold θ^*, and each investor stays if and only if his private signal is below a certain threshold x^*.

We then incorporate policy responses in a crisis and the formation of expectations by modeling interventions in our baseline setup as direct capital injections into funds experiencing run risks. θ is best interpreted as involving a solvency component or it concerns liquidity shock but intervention is not costless, and we capture in reduced-form the cost of intervention of scale m by $k(m)$. Many crisis interventions indeed entail significant costs. For example, Duygan-Bump et al. (2013) discuss how AMLF and CPFF were essentially capital injections that alleviated funds' pressure to meet redemption without suffering fire sales. Other examples include the Economic Stimulus Act of 2008, which reduced firms' tax obligations directly, and the Troubled Asset Relief Program (TARP), which intended to improve the liquidity of hard-to-value assets through secondary-market mechanisms. In Section 5.3, we discuss how our setup nests other forms of intervention. In almost all these cases, the intervention is not simply a costless promise but entails putting aside or using the funding. The equilibrium θ^* increases strictly with the size of the government's intervention: A greater liquidity injection makes the fund more likely to survive. Therefore, in a static economy, a benevolent government trades off this contemporaneous benefit and intervention costs.

In a dynamic setting, government intervention in the first period alters the informational environment in the second period. Agents' prior beliefs on θ are truncated, because whether the fund fails during the first period is public information. When the fund has survived in the first period, agents learn $\theta < \theta_1^*$, and their belief on θ shifts downward, making coordination easier. The opposite holds if the fund has failed in the first period. To the extent this public signal is useful, initial success increases the likelihood of subsequent success, and initial failure increases the likelihood of subsequent failure, endogenously giving rise to the greater tendency for the correlation of coordination outcomes across different periods — the "endogenous correlation effect." Initial intervention is thus more important because it increases the probability of survival in both periods.

Initial intervention also has an informational cost and, thus, its magnitude must be tempered. When a large intervention leads to a fund's survival, investors may infer the outcome is due to the intervention itself and not strong fundamentals. Conversely, if the fund fails despite a large initial intervention, investors become even more pessimistic about the market's fundamentals. This "conditional inference effect" harms investors' welfare and drives the government to intervene less for more favorable conditional updates. Therefore, the optimal policy has to consider the initial intervention's informational effect and

[1] See Schmidt et al. (2016) for more details on the run on MMMFs. As discussed in Bernanke (2015, p. 283), the government was keenly aware that AIG's failure could affect market participants' beliefs and lead to runs in other markets, just like Lehman's commercial paper had triggered the run on money market funds.

[2] One can view regional foreclosures as broadly analogous to "runs" due to the negative externality of a particular foreclosure on the values of neighboring properties. For example, Campbell et al. (2011) document a negative spillover effect of 1% per new foreclosure within a 0.10-mile radius. Guiso et al. (2013) document the prevalence of strategic defaults during this period.

trade off the two competing forces: intervening more to increase the likelihood of good news (truncating θ from above) and intervening less initially to encourage more favorable conditional updates (lower θ^*).

We establish results on the existence and uniqueness of equilibrium and study the implications for the optimal policy of a benevolent government. When the intervention costs are comparable in the sense that the endogenous intervention amounts are similar even absent public learning, the endogenous correlation effect dominates. Optimal policy then generally emphasizes initial intervention, that is, the scale of intervention in the first period always exceeds that in the second period, to kill two birds with one stone (improving fund survival in both periods).

This result also implies that a decision maker who neglects the informational externality of one intervention on another would under-intervene initially. However, when the intervention costs across the two periods differ drastically, so much so that survival in the first period does not guarantee survival in the second period (when the second-period cost is too high relative to the first and private signals are relevant for the marginal investor), nor does failure lead to failure (when the second-period cost is so low that one can intervene more despite the negative update from the first period's failure), the conditional inference effect can dominate. The more the government considers the informational externality, the more it shades intervention. This result also applies to countries and regions sharing common fundamentals in which one country's investors learn from another country's intervention outcome. In that sense, a global social planner (e.g., the European Union) could have a role in mitigating inefficient interventions in member countries or states.

Finally, when the government endogenously chooses interventions in funds of different sizes and that choice also determines the order of the realizations of coordination outcomes, the larger fund is "too big to save first" if the government can decide on the order that these coordination outcomes get realized, because it costs less to intervene in the smaller fund first to induce the same updating on the fundamental θ, and the larger fund benefits more from the reduced uncertainty. Even when the order of the realizations of coordination outcomes is exogenous, it can be beneficial to help the smaller fund disproportionally more relative to its size and likelihood of realizing the coordination outcome first. This result complements studies on institutions deemed "too big to fail" in that though bigger funds could be systemically important, helping smaller funds more or early could be more effective in terms of influencing the informational environment.

This paper contributes to our understanding of how interventions shape the informational environment during a crisis, and hence is useful for studying and assessing policies that aim to avoid inefficient outcomes. In particular, we highlight the role of government intervention on information structure: It not only affects the probability of good news versus bad news, but also the informativeness of news. It thus complements existing work on government interventions in markets with strategic complementarity. For example, Acharya and Thakor (2016) consider how liquidation decisions by informed creditors of one bank signal systematic shocks to other creditors and create contagions and how selective bailout could be efficient when the regulator observes the systematic shock. Huang (2016) studies how the interaction between a policy maker's reputation building and speculators' learning of the policy maker's type determines speculative attacks and regime changes. Regarding the design of intervention policy, Bebchuk and Goldstein (2011) examine the effectiveness of various forms (instead of the extent) of exogenous government policies in avoiding self-fulfilling credit market freezes. Sakovics and Steiner (2012) analyze who matters in coordination failures and how to set intervention targets. Choi (2014) shows the importance of bolstering stronger financial institutions to prevent contagion. Like these studies that focus on one particular aspect of intervention, we demonstrate how information structure design should play an important role in formulating intervention policies and should be considered together with previously discussed factors. In addition, this paper concerns the dynamic interaction of multiple endogenous interventions under general cost functions.

This paper is also related to global games and equilibrium selection (Carlsson and Van Damme, 1993; Morris and Shin, 1998), especially in dynamic settings (Frankel and Pauzner, 2000; Angeletos et al., 2007), with the government as a large player (Corsetti et al., 2004; Angeletos et al., 2006). Our paper adds to earlier studies by explicitly modeling the government as a large player that endogenously selects coordination equilibrium through both static and dynamic channels. Thus, we provide theoretical insights on how endogenous interventions relate to one another. Different from Angeletos et al. (2006) who demonstrate that endogenous intervention signals government type and leads to equilibrium multiplicity, our paper explores how endogenous intervention shapes information structure instead of signaling government's private information. This paper is also related to Angeletos et al. (2007) which extends global games to a dynamic setup in which agents take actions over multiple periods and can learn about the fundamental over time. The authors point out that multiplicity resurfaces from the interaction between endogenous learning based on regime survivals and exogenous learning induced by private news arrivals.[3] We introduce endogenous interventions, which lead to endogenous equilibrium multiplicity and selection, and show that the policy and public learning influence each other and have profound implications on the optimal policy design and coordination outcomes.

Finally, this paper adds to the emerging literature that apply information design and Bayesian persuasion (e.g., Gentzkow and Kamenica 2011; Bergemann and Morris 2017) to financial institutions and markets (e.g., Azarmsa and Cong 2018; Orlov et al. 2018). Related is Goldstein and Huang (2016), in which policy-makers costlessly design in-

[3] The Bayesian learning from public signals without endogenous government actions has also been discussed in several other papers. For example, Manz (2010) studies information contagion; Ahnert and Bertsch (2015) study information choice and contagion after wake-up-calls; Taketa (2004), studies contagion via a common investor base; Li and Ma (2016) study contagion and fire sales after a bank run.

formation in a one-shot intervention in which the information transmission relies on the truncation of beliefs as in Angeletos et al. (2007) but is endogenous. Lenkey and Song (2016) also analyze the tradeoffs in information design to study how a redemption fee affects runs on financial institutions when investors are asymmetrically informed about fundamentals. Our paper adds by introducing costly information design and underscoring its role in determining optimal information structure and dynamic policy (as well as characterizing the trade-offs in information design more analytically). To our best knowledge, we are the first to derive implications of the informational link between multiple endogenous interventions and the endogenous correlation effect of information design. Furthermore, the role of relative intervention costs is entirely new.

The rest of the paper is organized as follows: Section 2 lays out the basic framework and establishes a static benchmark. Section 3 characterizes the equilibrium in dynamic settings. Section 4 solves for the optimal policy and presents its implications. Section 5 discusses the results and extends the model. Section 6 concludes. The Online Appendix contains all the proofs and some model extensions.

2. Model

This section introduces the model with a representative intervention form: government directly infusing liquidity into funds subject to runs in each period. We start by analyzing a static model as our benchmark in Section 2.1 and move to the dynamic setting in Section 2.2.

2.1. Static benchmark

We introduce the benchmark setup, then analyze investors' stage game given the intervention, before finally examining the optimal intervention policy.

2.1.1. Model setup

A fund has a continuum of investors indexed by i and normalized to unit measure. Each investor has 1 unit of capital invested in the fund and simultaneously chooses between two actions: stay ($a_i = 1$) or withdraw ($a_i = 0$). For the remaining analysis, we interpret withdrawal as a run on the fund, and staying can be interpreted as rolling over short-term debts. The net payoff from running on the fund and investing the proceeds in an alternative vehicle (e.g., a Treasury bill) is always equal to r, and the payoff to each investor from staying is R if the fund survives the run ($s = S$) and zero if the fund fails ($s = F$). Let $R > r > 0$. An investor finds it optimal to stay if and only if she expects the probability of survival to exceed the cost of illiquidity, defined as $c \equiv \frac{r}{R}$. Table 1 shows the net payoff of each action under different states and actions and when we normalize the payoff matrix by subtracting r and scaling by $\frac{1}{R}$. For notational convenience, we use the normalized net payoffs for the remainder of the paper and extend them to alternative payoff structures in Online Appendix Section D.3.

Agents' decisions are complements: the fund is more likely to survive as more agents choose to stay. The fund

Table 1
Net payoffs and normalized net payoffs.
R denotes the payoff to each investor from staying if the fund survives the run ($s = S$). r denotes the net payoff from running on the fund and investing the proceeds in an alternative vehicle. Note that $R > r > 0$. c denotes the cost of liquidity, defined as $c \equiv \frac{r}{R}$.

	Net payoff		Normalized net payoff	
Outcome	Stay	Run	Stay	Run
Survive	R	r	$1 - c$	0
Fail	0	r	$-c$	0

survives if and only if

$$A + m \geq \theta, \tag{1}$$

where A represents total measure of agents who choose to stay. $m \in [0, \bar{m}]$ is the size of the government's capital injection to the fund and is bounded above by a constant $\bar{m} > 0$. $\theta \in \mathbb{R}$ summarizes the underlying fundamental. Note that we assume the government publicly commits to the intervention. In the context of the run on MMMFs in 2008, $1 - A$ would represent the volume of net redemption of fund shares, and m represents the magnitude of government intervention, such as insurance offerings and purchase facilities. θ represents the fundamental of the underlying assets, which is best interpreted as a shortfall in the fund's interim revenue that must be overcome to continue the investments. In that regard, the shock is similar to the so-called liquidity shock in Holmström and Tirole (1998) but, in essence, entails a solvency component. For the fund to survive, the total resource $A + m$ must dominate the fundamental shock θ.

The government cares about social welfare composed of investors' total payoff less the intervention cost $k(m)$, which is weakly increasing and convex. $k(m)$ captures the political capital expended, tax distortion, and moral hazard associated with the intervention policy, as well as the amount of m used in the intervention. In our baseline, we should think of $k(m)$ as nontrivial, and it becomes so large that intervening more than $\bar{m}$ is infeasible. Oftentimes, the intervention amount m is used. For example, during the money market fund run in 2008, the Fed implemented the Asset-Backed Commercial Paper Money Market Fund Liquidity Facility, a lending program for troubled money market funds, which lent out \$150 billion in the first ten days of operation. Resources are actually spent and could be very costly for the Fed because the facility could lose money due to bad fundamentals of the funds' assets. Another example is the Troubled Asset Relief Program (TARP), which allows the government to purchase toxic assets and equity from financial institutions to strengthen the financial sector and to address the subprime mortgage crisis. Like many other intervention programs during the global recession, TARP operated primarily through secondary markets and entailed investing the resources. Moreover, intervention costs and political constraints are real, at least at the onset of the crisis (Swagel, 2015). Setting aside resources may require approval from relevant committees. Moral hazard and tax distortions can also add to the cost. In Online Appendix Section D.2, we model fund managers' actions and microfound the cost using moral hazard induced by interventions. All these considerations rule out the simple solution of promising an unlimited amount of m at no cost, which would have worked for a pure liquidity crisis.

Coordination is needed when both θ and m are commonly known by all agents. If $\theta - m \in (0, 1)$, two equilibria coexist. In one equilibrium, all investors stay and, in the other one, all investors run. Global games resolve this issue of equilibrium multiplicity through introducing incomplete information. We apply the same technique to assume agents each observe a noisy private signal of θ. Agent i observes

$$x_i = \theta + \varepsilon_i, \tag{2}$$

where the noise $\varepsilon_i \sim Unif[-\delta, \delta]$ is independent and identically distributed across investors. For simplicity, we assume the prior distribution of θ is uniform on $[-B, B]$, where $B \gg \max\{\delta, \bar{m}\}$.[4] We also assume the government does not know the realization of the fundamental θ and does not have a private signal about it, which allows us to abstract away from signaling and focus on intervention as a form of information design.[5]

The timing in this single-period game is as follows. The government announces m and then each investor i receives a private signal x_i and plays the game of choosing whether to stay, before payoffs are realized. We restrict the equilibrium set to symmetric Perfect Bayesian Equilibria (PBE) in monotone strategies. All agents' strategies are symmetric and monotonic with respect to x and m. Agent i's strategy $a_i(x_i, m)$ is nonincreasing in x_i and nondecreasing in m. We first examine the equilibrium given the government's intervention m. For the remainder of this paper, we refer to this game as investors' stage game.

2.1.2. Investors' stage game given intervention

Because $B \gg \max\{\delta, \bar{m}\}$, it is without loss of generality to further restrict the equilibrium set to threshold equilibria denoted by (θ^*, x^*). The fund survives if and only if $\theta \le \theta^*$, and each investor stays if and only if his signal $x \le x^*$. Lemma 1 summarizes the equilibrium outcome in the static game.

Lemma 1. In the stage game, $\forall m \in [0, \bar{m}]$, there exists a unique symmetric PBE in monotone strategies (θ^*, x^*), where

$$\begin{cases} \theta^* & = 1 + m - c \\ x^* & = 1 + m - c + \delta(1 - 2c). \end{cases} \tag{3}$$

Each investor's strategy follows $a_i = \mathbb{1}\{x_i \le x^*\}$. The fund's outcome $s = S$ if $\theta \le \theta^*$ and $s = F$ otherwise.

According to Lemma 1, the fund survives if and only if $\theta \le \theta^*$. Each agent stays if and only if his private signal $x_i \le x^*$. θ^* increases in m and so does x^*. In other words, the fund is more likely to survive and investors are more inclined to stay if the size of government intervention increases. This result shows the static effect of government intervention on coordination. In Section 3, we show government intervention has dynamic coordination effects.

2.1.3. Welfare and optimal intervention

Let V_i be investor i's net payoff, and $W = E\left[\int_0^1 V_i di\right]$. Then investors' welfare is

$$W = \frac{1}{2B}\Bigg[\underbrace{\int_{-B}^{\theta^*} (1-c)d\theta}_{\text{Fundamental}} - \underbrace{\int_{x^*-\delta}^{\theta^*} (1-c)\left(1 - \frac{x^* - (\theta - \delta)}{2\delta}\right)d\theta}_{\text{Overrun}} - \underbrace{\int_{\theta^*}^{x^*+\delta} c\frac{x^* - (\theta - \delta)}{2\delta}d\theta}_{\text{Underrun}}\Bigg]. \tag{4}$$

In the payoff function, $\frac{1}{2B}$ is the probability density of the uniform distribution. The terms inside the square bracket split into three terms. The first term, *Fundamental*, equals the net payoff if all agents stay when the fund survives. The second term, *Overrun*, represents the net payoff loss due to the fact that some agents choose to run when the fund survives. The last term, *Underrun*, is the net loss from agents who choose to stay when the fund fails.

Simple calculation suggests that the total welfare is

$$W - k(m) = \frac{(1-c)[1 + B - c(1+\delta) + m]}{2B} - k(m). \tag{5}$$

The marginal benefit of m on W is a constant, $\frac{(1-c)}{2B}$. This result comes from the fact that an increase in m also raises θ^* linearly, making the fund more likely to survive. $\frac{(1-c)}{2B}$ is the net payoff from staying $1 - c$, scaled by the probability density $\frac{1}{2B}$. Therefore, intervention improves coordination. Because m lies in a compact set, an optimal intervention always exists:

$$m^* = \sup\left\{m \in [0, \bar{m}] : \lim_{\epsilon \to 0} \frac{k(m+\epsilon) - k(m)}{\epsilon} \le \frac{1-c}{2B}\right\}. \tag{6}$$

For example, if $k(m) = \frac{1}{2}zm^2$, then $m^* = \min\left\{\frac{1-c}{2zB}, \bar{m}\right\}$.

2.2. Dynamic economy

We now extend the static model to a two-period dynamic economy. In each period, a unit measure of agents

[4] We assume B is sufficiently large relative to $\bar{m}$ so that the government cannot guarantee a successful intervention. Uninformative prior corresponds to $B \to \infty$. This is just an alternative way of saying $k(m)$ is large when m is large. It allows us to apply our model even to situations in which θ is a pure liquidity shock, because a weak government's unlimited promise of insurance is not always credible (the promised amount can break the government or the insuring institution). One example is discussed in He and Manela (2016): Half of running Washington Mutual (WaMu) depositors were covered by the insurance from the Federal Deposit Insurance Corporation (FDIC), and depositors may worry that FDIC could not afford to cover WaMu's insured deposits, which were several times the Deposit Insurance Fund at the time. Iyer and Puria (2012) also show that deposit insurance is only partially effective in preventing runs.

[5] Essentially, we are assuming institutional investors are typically more informed than the government about the fundamental state of the market, which is consistent with Diamond and Kashyap (2015) (financial institutions know more about the fundamental illiquidity), Bond and Goldstein (2015) (government relies on market prices to learn fundamentals), Sakovics and Steiner (2012) (governments' inferior knowledge on utilizing or allocating resources leads to tax and subsidy distortions), and Bernanke (2015) (government is uncertain about how the market reacts to intervention).

chooses whether to stay or run on a fund (not necessarily the same fund across the two periods). The government intervenes in each period with m_1 and m_2. Agents in period 2 observe whether the first fund survives in period 1. To focus on Bayesian learning from public intervention outcomes, we assume the mass of agents in each period is nonoverlapping, in that they do not observe the private signals in other periods. The government's cost of intervention now is $K(m_1,\ m_2)$, which is weakly increasing and convex in both arguments, and satisfies $K(0,0)=0$, where $\{m_1,\ m_2\}\in I$ and $I\subset R^2$ indicates a convex set of feasible interventions. For ease of exposition, we assume for the remainder of the paper that the cost function lies in the space $\mathcal{C}[0,\bar{m}_1]\ \times\ \mathcal{C}[0,\bar{m}_2]$, where $\bar{m}_1$ and $\bar{m}_2$ are finite constants.

Importantly, the two periods are linked in the following sense. First, the fundamentals $\{\theta_t\}_{t=1,2}$ are identical across two periods. We omit the subscript of θ from now on and relax the assumption in Section 5.1 by requiring only positively correlated fundamental. Second, agents in period 2 also observe the public outcome of whether investment has succeeded in the first period, indicated by $s_1=S$ or $s_1=F$. Third, the costs of intervention across these two periods can interact with each other.

The government chooses interventions to maximize investors' welfare, subtracting the intervention cost $K(m_1,\ m_2)$. In each period, agents simultaneously choose whether to stay with the fund ($a_t=1$) or to run ($a_t=0$). Because we focus on symmetric equilibrium, the subscript i for agent i is omitted without any confusion. The period-by-period normalized payoff structure is identical to the static game. Running ($a_t=0$) always guarantees zero payoff, and staying ($a_t=1$) pays off $1-c$ in survival and $-c$ in failure. Agents' decisions within the same period are complements. Investment in period t succeeds if and only if

$$A_t+m_t\geq\theta, \tag{7}$$

where A_t is the total measure of investors who choose to invest and m_t denotes the size of liquidity injected by the government. Again, θ represents the fundamental. Similar to the interpretation of the static game, the runs could represent runs on MMMF and financial commercial papers, with θ representing the market-wide illiquidity or the credit quality of commercial paper issuers.

The timing within each period goes as follows. The government announces m_t. Then, each investor i in period t receives a private signal $x_{it}=\theta+\varepsilon_{it}$ about the fundamental, where $\varepsilon_{it}\sim Unif[-\delta,\delta]$. Finally, investors choose whether to stay, and their payoffs realize. The setup is dynamic in the sense that period 1's outcome is revealed before investors take actions in period 2.

In the baseline, we study a problem in which the government maximizes welfare by solving

$$\max_{m_1\in[0,\bar{m}_1],m_2\in[0,\bar{m}_2]} E\left[\int_0^1 V_{1i}di+\int_0^1 V_{2i}di\right]-K(m_1,m_2). \tag{8}$$

Given that the set $[0,\bar{m}_1]\times[0,\bar{m}_2]$ is compact, an optimal policy exists in general, which exhibits interesting features. We solve this problem in two steps. Section 3 takes government interventions $(m_1,\ m_2)$ as given and derives the stage game equilibrium. Section 4 examines a benevolent government's optimal policy design.

3. Coordination equilibrium

We first examine the stage game of investors' coordination in each period, taking the intervention $\{m_1,\ m_2\}$ as given. Our equilibrium concept is symmetric Perfect Bayesian Equilibrium in monotone strategies. All agents' strategies are symmetric and monotonic with respect to x_t and m_t: Agent i's strategy in period t, $a_{it}(x_{it})$, is nonincreasing in x_{it} and nondecreasing in m_t, $t=1,2$.

3.1. Equilibrium and social welfare in period 1

The analysis in period 1 is identical to the static game. We relabel the unique threshold equilibrium with time subscripts $\left(\theta_1^*,x_1^*\right)=(1+m_1-c,1+m_1-c+\delta(1-2c))$. The fate of the fund is $s_1=S$ if $\theta\leq\theta_1^*$, and $s_1=F$ otherwise. Agent i adopts a threshold strategy $a_{i1}=\mathbb{1}\left\{x_{i1}\leq x_1^*\right\}$.

The social welfare in period 1 is also identical to the static economy,

$$W_1-K(m_1,0)=\frac{(1-c)[1+B-c(1+\delta)+m_1]}{2B}-K(m_1,0). \tag{9}$$

3.2. Equilibrium in period 2

In period 2, the outcome of period 1 intervention (henceforth referred to as public news) is publicly known. As a result, beliefs on θ are truncated either from above or from below.

Even though multiple equilibria easily emerge in dynamic global games (Angeletos et al., 2007), we show in our baseline model that when signals are imprecise but still reasonably informative, we obtain a unique equilibrium that more clearly conveys the main economic intuition of our paper. To that end, we assume $2\delta>1$ and $\frac{1}{2\delta+1}<c<\frac{2\delta}{1+2\delta}$ for the remainder of the paper. These assumptions correspond to the fact that, during crisis, uncertainty is high and the cost of illiquidity is in an intermediate range in which agents do not overwhelmingly prefer to stay or to run. These assumptions ensure a unique threshold equilibrium in period 2 for both $s_1=S$ and $s_1=F$ and for all values that m_1 and m_2 take on. In Online Appendix Section D.1, we discuss the equilibrium outcomes for general δ and c, relate our findings to Angeletos et al. (2007), and explain what factors determine equilibrium multiplicity in our model and in the literature.

3.2.1. Survival news

If the fund in period 1 has survived ($s_1=S$), the prior belief on θ is bounded above at θ_1^*: $\theta\sim Unif\left[-B,\theta_1^*\right]$. In this case, investors could stay regardless of their signals. In fact, this equilibrium exists if and only if $m_2>m_1-c$. In this equilibrium, the (hypothetical) threshold x_2^* satisfies $x_2^*\geq\theta_1^*+\delta$, which is always above all agents' realized signals. We call such an equilibrium a stage game equilibrium with dynamic coordination because the government's intervention in the first period has a dominant effect on improving coordination among investors in the second period.

Lemma 2 (stage game equilibrium with dynamic coordination). *If $s_1 = S$, $\left(\theta_2^*, x_2^*\right) = \left(\theta_1^*, \theta_1^* + \delta\right)$ constitutes an equilibrium if and only if $m_2 > m_1 - c$.*

Now that $\theta \le \theta_1^*$ is common knowledge, any equilibrium with $\left(\theta_2^* > \theta_1^*, x_2^* > \theta_1^* + \delta\right)$ is equivalent to one with $\left(\theta_2^*, x_2^*\right) = \left(\theta_1^*, \theta_1^* + \delta\right)$.

Next, we turn to threshold equilibria with $\theta_2^* < \theta_1^*$ so that the fate of the fund in period 2 still has uncertainty. Likewise, any threshold equilibrium $\left(\theta_2^*, x_2^*\right)$ necessarily satisfies two conditions. First, when $\theta = \theta_2^*$, the fund is about to fail, that is, $A_2 + m_2 = \Pr\left(x_2 < x_2^* \middle| \theta = \theta_2^*\right) + m_2 = \theta_2^*$. Second, the marginal agent who receives the signal x_2^* is indifferent between stay and run, $\Pr\left(\theta \le \theta_2^* \middle| x_2 = x_2^*, \theta \in \left[-B, \theta_1^*\right]\right) = c$.

We analyze the equilibrium in two cases, depending on whether the marginal investor finds the public news useful. Ignoring the public news, the marginal investor's posterior belief on θ is simply $\Pr\left(\theta \middle| x_2 = x_2^*\right) \sim Unif\left[x_2^* - \delta, x_2^* + \delta\right]$. If $x_2^* + \delta < \theta_1^*$, then the marginal investor finds the public news useless because it does not also help him learn about θ, that is, $\Pr\left(\theta \le \theta_2^* \middle| x_2 = x_2^*, \theta \in \left[-B, \theta_1^*\right]\right) = \Pr\left(\theta \le \theta_2^* \middle| x_2 = x_2^*\right)$. We call such an equilibrium a stage game equilibrium without dynamic coordination because intervention in the first period has no effect on coordination in the second period.

Lemma 3 (stage game equilibrium without dynamic coordination). *If $s_1 = S$ and $m_2 < m_1 - 2\delta(1 - c)$, an equilibrium with thresholds $\left(\theta_2^*, x_2^*\right)$ exists, in which*

$$\begin{cases} \theta_2^* = 1 + m_2 - c \\ x_2^* = 1 + m_2 - c + \delta(1 - 2c). \end{cases} \tag{10}$$

In this case, the dynamic game is simply a repeated version of the static game. This is not surprising because the public news is useless. However, if $x_2^* + \delta > \theta_1^*$, the marginal investor finds the public news useful, that is, $\Pr\left(\theta \le \theta_2^* \middle| x_2 = x_2^*, \theta \in \left[-B, \theta_1^*\right]\right) \ne \Pr\left(\theta \le \theta_2^* \middle| x_2 = x_2^*\right)$. We call this equilibrium a stage game equilibrium with partial dynamic coordination because government intervention in the first period partially influences the coordination among investors in the second period. Equilibrium without dynamic coordination is an artifact of bounded noise in the private signals. For unbounded noise, equilibrium always involves at least partial dynamic coordination.

Lemma 4 (stage game equilibrium with partial dynamic coordination). *If $s_1 = S$ and $m_1 - 2\delta(1 - c) < m_2 < m_1 - c$, an equilibrium exists with thresholds*

$$\begin{cases} \theta_2^* = 1 + m_2 - c + \frac{c[m_2 - m_1 + 2\delta(1-c)]}{2\delta - c(1+2\delta)} \\ x_2^* = 1 + m_2 - c + \delta(1 - 2c) + \frac{c(1+2\delta)[m_2 - m_1 + 2\delta(1-c)]}{2\delta - c(1+2\delta)}. \end{cases} \tag{11}$$

Simple comparisons show that with partial dynamic coordination, both θ_2^* and x_2^* are higher than their counterparts in the case without dynamic coordination. Therefore, the fund is more likely to survive, and investors are more likely to stay compared with the case without dynamic coordination. Intuitively, the public news that $\theta < \theta_1^*$ has eliminated the possibility of θ being too high so that, in equilibrium, investors who take such elimination into account will behave more aggressively by choosing a higher threshold x_2^*. As a result, more investors tend to stay for a given θ, and the fund is more likely to survive due to the increasing coordinated decisions to stay.

Combining Lemmas 2, 3, and 4, Proposition 1 describes the equilibrium outcome given any (m_1, m_2) and $s_1 = S$.

Proposition 1 (equilibrium in period 2 when $s_1 = S$).

1. *If $m_2 < m_1 - 2\delta(1 - c)$, the unique equilibrium is the stage game equilibrium without dynamic coordination.*
2. *If $m_1 - 2\delta(1 - c) < m_2 < m_1 - c$, the unique equilibrium is the stage game equilibrium with partial dynamic coordination.*
3. *If $m_1 - c < m_2$, the unique equilibrium is the stage game equilibrium with dynamic coordination.*

The intuition for the results is as follows. First, ignore the public news from period 1 that $\theta \in \left[-B, \theta_1^*\right]$ so that the equilibrium in period 2 is without dynamic coordination. Then, the cutoffs $\left(\theta_2^*, x_2^*\right) = (1 + m_2 - c, 1 + m_2 - c + \delta(1 - 2c))$ are similar to those in the period 1 equilibrium. From the marginal investor's perspective, the true $\theta \in \left[x_2^* - \delta, x_2^* + \delta\right]$. If it further holds that $x_2^* + \delta < \theta_1^*$ [when $m_2 < m_1 - 2\delta(1 - c)$], the marginal investor's private signal dominates his inference on θ from the public news. In other words, the public information that $\theta < \theta_1^*$ does not further help him infer the true distribution of θ on top of this private signal.

Next, consider the case in which the marginal investor finds the information at least partially useful, in which case both thresholds $\left(\theta_2^*, x_2^*\right)$ are augmented (See Lemma 4). If it further holds that $\theta_2^* > \theta_1^*$ (when $m_2 > m_1 - c$), the second fund survives for sure because θ is known to be lower than θ_1^*. In this case, the public news dominates the private signal.

3.2.2. Failure news

If the fund in period 1 has failed ($s_1 = F$), the prior belief on θ is bounded below at θ_1^*: $\theta \sim Unif\left[\theta_1^*, B\right]$. Proposition 2 summarizes the equilibrium outcome in this case. The detailed derivation can be found in Online Appendix Section B. In the stage game equilibrium with dynamic coordination, investors choose to run regardless of their signals. The intuitions for different cutoffs are similar to those in Proposition 1.

Proposition 2 (equilibrium in period 2 when $s_1 = F$).

1. *If $m_2 < m_1 + 1 - c$, the unique equilibrium is the stage game equilibrium with dynamic coordination.*
2. *If $m_1 + 1 - c < m_2 < m_1 + 2c\delta$, the unique equilibrium is the stage game equilibrium with partial dynamic coordination.*
3. *If $m_1 + 2c\delta < m_2$, the unique equilibrium is the stage game equilibrium without dynamic coordination.*

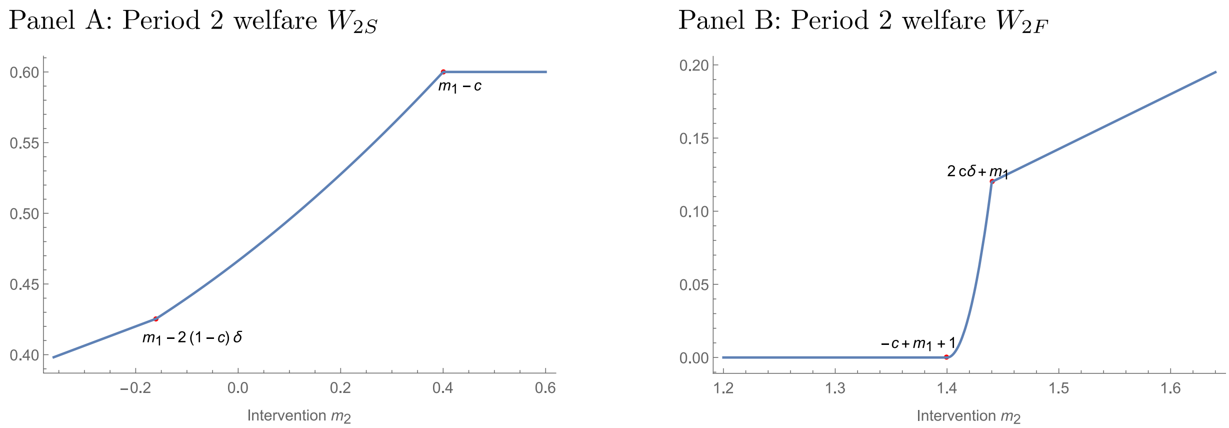

Fig. 1. W_{2S} **and** W_{2F} **as a function of** m_2. This figure plots investors' welfare in period 2 (W_{2S}, W_{2F}) as a function of m_2, the size of government intervention in that period. Panels A and B, respectively, plot the welfare function when the fund has survived (W_{2S}) and failed (W_{2F}) in the first period. Both welfare functions are increasing in m_2. Parameters are $\delta = 0.8,\ c = 0.4,\ B = 3,$ and $m_1 = 0.8$.

3.2.3. Investors' welfare and dynamic coordination

Let $W_{2S} = E\left[\int_0^1 V_{2i} di \middle| s_1 = S\right]$ be the total expected payoff in period 2 conditional on $s_1 = S$. Also, let $W_{2F} = E\left[\int_0^1 V_{2i} di \middle| s_1 = F\right]$ be the total expected payoff in period 2 when $s_1 = F$. Applying results from Propositions 1 and 2, we are able to obtain W_{2S} and W_{2F} for given values of m_1 and m_2. Corollary 1 below shows the results.

Corollary 1 (investors' welfare in period 2).

1. *Conditional on* $s_1 = S$,
   (a) *If* $m_2 < m_1 - 2\delta(1-c)$, $W_{2S}^{nc} = \frac{(1-c)[1+B-c(1+\delta)+m_2]}{B+\theta_1^*}$.
   (b) *If* $m_1 - 2\delta(1-c) < m_2 < m_1 - c$,
   $W_{2S}^{pc} = \frac{1-c}{\theta_1^*+B}\left[\theta_1^* + B + \frac{\delta c(c-m_1+m_2)^2 + 2\delta(c-m_1+m_2)[2\delta - c(1+2\delta)]}{[2\delta - c(1+2\delta)]^2}\right]$.
   (c) *If* $m_2 > m_1 - c$, $W_{2S}^{c} = (1-c)$.
2. *Conditional on* $s_1 = F$,
   (a) *If* $m_2 < m_1 + 1 - c$, $W_{2F}^{c} = 0$.
   (b) *If* $m_1 + 1 - c < m_2 < m_1 + 2c\delta$, $W_{2F}^{pc} = \frac{1-c}{B-\theta_1^*}\frac{c\delta(-1+c-m_1+m_2)^2}{(-1+c+2c\delta)^2}$.
   (c) *If* $m_2 > m_1 + 2c\delta$, $W_{2F}^{nc} = \frac{1-c}{B-\theta_1^*}(m_2 - m_1 - c\delta)$.

The superscripts of W_{2S} and W_{2F} refer to equilibrium types. *nc*, *pc*, and *c*, respectively, stand for stage game equilibrium without dynamic coordination, with partial coordination, and with coordination. The expression of W_{2S}^{nc} is isomorphic to W_1, except that the denominator is replaced by $\theta_1^* + B$ because the period 1 outcome is informative of the distribution of θ. W_{2S}^{pc} includes an additional positive term $\frac{\delta c(c-m_1+m_2)^2 + 2\delta(c-m_1+m_2)[2\delta - c(1+2\delta)]}{[2\delta - c(1+2\delta)]^2}$, which captures the investors' increasing coordinated decision to stay due to the public information. Thus, $W_{2S}^{pc} > W_{2S}^{nc}$. Finally, with coordination, all investors stay irrespective of their signals and, thus, $W_{2S}^{c} = 1 - c$. W_{2F} can be interpreted similarly.

Panel A of Fig. 1 plots W_{2S} against m_2, including the welfare function in all three different types of equilibria. Given m_1, W_{2S} is continuous, increasing in m_2, and convex in the region that involves partial dynamic coordination. Unlike in the first period, the marginal effect of m_2 on W_{2S} is no longer a constant. Initially, W_{2S} increases linearly in m_2, in which case the intervention in the first period has no dynamic coordination effect. When $m_1 - 2\delta + 2c\delta < m_2 < m_1 - c$, the marginal effect of m_2 is increasing, due to the dynamic coordination effect of period 1 intervention. When $m_2 > m_1 - c$, the dynamic coordination effect is maximized and all agents' decisions are well coordinated toward an equilibrium without any run. In that case, further increasing m_2 has no effect.

Panel B of Fig. 1 plots W_{2F} against m_2, including the welfare function in all three different types of equilibria. Given m_1, W_{2F} is continuous, increasing in m_2, and convex when the equilibrium involves partial dynamic coordination. The effect of m_2 on W_{2F} is not a constant either. When $m_2 < m_1 + 1 - c$, the failed intervention in period 1 makes all agents pessimistic. A slight increase in m_2 does not change peoples' belief and, therefore, the marginal effect of m_2 on W_{2F} is zero. When $m_1 + 1 - c < m_2 < m_1 + 2c\delta$, the marginal effect of m_2 on W_{2F} is positive and increasing. Finally, when $m_2 > m_1 + 2c\delta$, the dynamic effect is zero and W_{2F} increases linearly in m_2.

Clearly, m_1 affects both W_{2S} and W_{2F} by altering θ_1^* and, thus, the resulting informational structure. Because W_{2S} and W_{2F} are piecewise in m_1 and thus not everywhere differentiable, we define the left-hand derivative of W_{2S} and W_{2F} with respect to m_1 as the conditional inference effect, as Fig. 2 illustrates.

Proposition 3 (conditional inference effect). *Given* s_1 *and* m_2, *investors' welfare* W_{2S} *and* W_{2F} *decrease in* m_1.

The conditional inference effect implies that, given the outcome of the period 1 fund and given the government's intervention into the period 2 fund, higher initial intervention always decreases investors' welfare. This effect is consistent with the fact that the government often faces uncertainties on intervention outcomes and is aware of the informational detriments of using large interventions (e.g., Bernanke (2015, p. 282) on the intervention in AIG). The overall effect of m_1 on the unconditional $E[W_2]$ is nonmonotonic because, besides the conditional inference effect, the probability of $s_1 = S$ increases with m_1. Thus, to

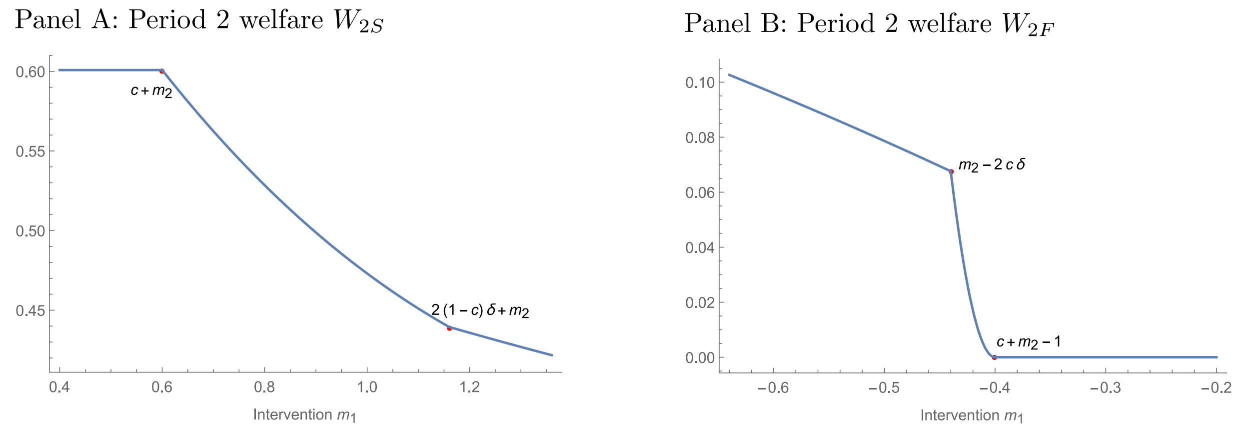

Fig. 2. W_{2S} **and** W_{2F} **as a function of** $\mathbf{m}_1$. This figure plots investors welfare in period 2 (W_{2S}, W_{2F}) as a function of m_1, the size of government intervention in period 1. Panels A and B, respectively, plot the welfare function when the fund has survived (W_{2S}) and failed (W_{2F}) in the first period. Both welfare functions are decreasing in m_1. Parameters are $\delta = 0.8,\ c = 0.4,\ B = 3,$ and $m_2 = 0.2$.

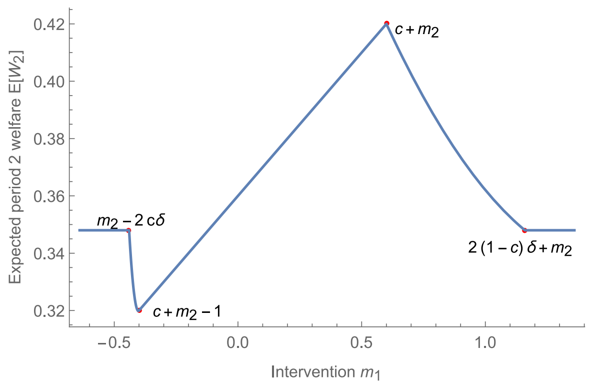

Fig. 3. $E[W_2]$ **as a function of** $\mathbf{m}_1$. This figure plots investors expected welfare in period 2 $E[W_2]$ as a function of m_1, the size of government intervention in period 1. The plot shows that the expected welfare peaks at $m_1 = m_2 + c$. Parameters are $\delta = 0.8,\ c = 0.4,\ B = 3,$ and $m_2 = 0.2$.

the extent that intervention outcomes are correlated across the two periods, increasing m_1 kills two birds with one stone. Fig. 3 shows this non-monotonic property by plotting $E[W_2] = \Pr(s_1 = S)W_{2S} + (1 - \Pr(s_1 = S))W_{2F}$ against m_1, taking m_2 as given. Clearly, the overall effect attains its highest level at $m_1 = m_2 + c$ and starts to decline afterward. The decline is intuitive. Conditional on s_1, a larger m_1 leads to a more negative update on θ_1^* because investors attribute the fund's survival more to the large intervention. They become pessimistic about the fundamental when the fund fails.

That said, the intervention outcomes are perfectly correlated if $c - 1 < m_1 - m_2 < c$. In this region, the stage game equilibrium features dynamic coordination whether the fund survives in the first period or not. If the intervention costs are similar across the two periods, the interventions $\{m_1, m_2\}$ also tend to be close to one another even without public learning (see Section 4). This force makes the public signal s_1 dominate over the private signal x_{i2}, leading to a greater tendency for highly correlated coordination outcomes, which we refer to as the endogenous correlation effect.

Proposition 4 (endogenous correlation effect). *Investors' welfare $E[W_2]$ increases in m_1 when $c - 1 < m_1 - m_2 < c$.*

To get the general intuition for this effect, it is useful to compare equilibrium thresholds across different types of stage game equilibria. When $s_1 = S$ and $m_2 \in (m_1 - 2\delta(1-c), m_1 - c)$, both x_2^* and θ_2^* in the stage game equilibrium with partial dynamic coordination (Lemma 4) exceed their counterparts in the stage game equilibrium without dynamic coordination (Lemma 3) but are less than those in the stage game equilibrium with dynamic coordination (Lemma 2). When the marginal agent finds the public news useful and realizes that the expected threshold level suggested by his signal alone is too stringent, he behaves more aggressively by choosing a higher threshold and running less often. As a result, θ_2^* is also higher and the fund is more likely to survive. When $s_1 = F$, both x_2^* and θ_2^* are the lowest (most stringent) in the stage game equilibrium with dynamic coordination, followed by the stage game equilibria with partial and no dynamic coordination. If we take coordination outcomes without dynamic learning as the benchmark, the dynamic coordination effect of initial intervention suggests that initial survival increases the likelihood of subsequent survival, and initial failure increases the likelihood of subsequent failure, which drives Proposition 4. Anecdotes during the recent financial crisis support the assertion that the policy makers place weights on the impact of one intervention on subsequent coordination outcomes.[6]

At the same time, within the regions of partial dynamic coordination, conditional inference effect dominates and $\mathbb{E}[W_2]$ is decreasing in m_1. Endogenous correlation matters more when we consider the types of news (good, bad,

[6] For example, Geithner (2014, p.215) recounts how requiring haircuts in FDIC's involvement in Washington Mutual (WaMu) makes the intervention weaker and how policy makers were concerned that the requirement could lead to a higher probability of failure, "more bank failures and much bigger FDIC losses down the road," and that "more failures would eventually require more aggressive government interventions." Bernanke (2015, p. 277) also says that "financial panics are a collective loss of the confidence essential for keeping the system functioning" and that the FDIC's sale of WaMu would likely trigger downgrades and worsen market beliefs.

irrelevant), whereas conditional inference matters more when we consider the quality variation within the same type of news. What then determines which effect dominates? The initial intervention outcome induces jumps in the belief in the second period's coordination outcome. Outside the region $c-1<m_1-m_2<c$, the jump is moderate and conditional inference weakly dominates. Otherwise, the jump is sufficiently big (posterior on the outcome becomes either zero or one) and creates discontinuity in the impact of conditional inference, leading to endogenous correlation dominating in the absence of conditional inference. In other words, as long as m_1 relative to m_2 is such that the news is extremely informative, agents care more about whether it is good news or bad news because the conditional inferences for different values of m_1 in this case are all the same.

In addition, the mechanism does not crucially rely on the distributional assumption of signals. For example, in the discussion of normally distributed signals in Online Appendix Section D.4, we show that there is still an equilibrium outcome with full dynamic coordination and one with partial dynamic coordination. Therefore, either endogenous correlation or conditional reference can dominate. In our model, the initial intervention essentially designs information for the subsequent intervention. Related is Goldstein and Huang (2016), which specializes to the case of costless information design for a single coordination game. In their setup, maintaining the regime too often reduces agents' positive updates, resembling our conditional inference effect. However, abandoning too often results in costly failures and, thus, should be avoided. We generalize this desire for good news to multiple interventions and derive the novel endogenous correlation effect of intervention outcomes. Because information design is costless, the policy maker optimally commits to abandoning the regime with a high enough frequency so that a regime maintenance results in no attack. Thus, maintenance leads to survival and, because the game ends if the regime is abandoned, abandonment leads to failure. We show that with costly information design and continuation game even upon initial failure, survival outcomes still tend to correlate. However, the correlation is in general imperfect and relative intervention costs matter. This phenomenon has profound implications when discussing endogenous intervention policy across countries or episodes of runs.

4. Dynamic intervention and optimal policy

The analysis so far has taken as given the government's interventions $\{m_1,\ m_2\}$ and studies investors' coordination for given interventions. In this section, we consider the government's problem. Given the costs and constraints of interventions, how should the government allocate resources across two periods, and how does the information structure channel affect the scale and sequence of interventions? This section discusses three key implications for the optimal policy: emphasis on initial intervention, under- and over-intervention by myopic governments, and saving smaller funds disproportionately more.

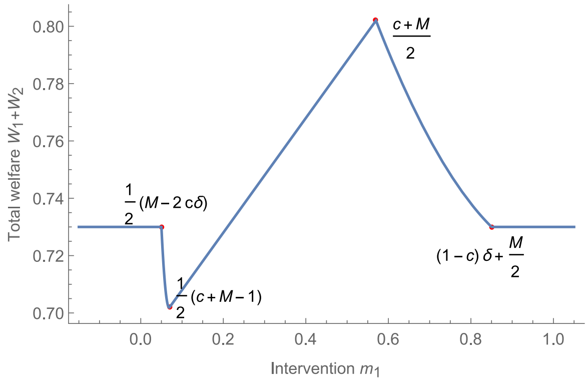

Fig. 4. W_1+W_2 **as a function of** m_1 $(m_1+m_2=M>2c\delta)$. This figure plots investors total welfare in two periods W_1+W_2 as a function of m_1, the size of government intervention in period 1. The government is assumed to have a total resource of M to be allocated across two periods. The plot shows that the total welfare peaks at $m_1=\frac{M+c}{2}$. Parameters are $\delta=0.8,\ c=0.4,\ B=3,$ and $M=0.74$.

Eq. (8) states the government's objective, which is to maximize all investors' payoff net the intervention cost. The government's strategy space is to choose $m_1\in[0,\bar{m}_1]$ and $m_2\in[0,\bar{m}_2]$ subject to the potential information set and implementation constraint. This section focuses on the case of committed intervention, which corresponds to choosing m_2 before s_1 is realized. In Section 5.2, we discuss how our main results and intuition carry through under some reasonable parameter ranges, for the case of contingent intervention that entails choosing m_2 after s_1 is realized. Committed intervention describes situations in which the government has to roll out policy programs or set up funding facilities before knowing the outcome of previous interventions, as was the case in the recent crisis.

4.1. Emphasis on initial intervention

First consider a special case in which the government has a total budget M that can be used across the two periods, which admits explicit solutions. In other words, $K(m_1,m_2)=\frac{\mathbb{I}_{\{m_1+m_2>M\}}}{1-\mathbb{I}_{\{m_1+m_2>M\}}}$. A benevolent government solves the problem

$$\max_{m_1,m_2} W=E\left[\int_0^1 V_{1i}di+\int_0^1 V_{2i}di\right] \tag{12}$$

$$s.t.\ m_1+m_2=M. \tag{13}$$

We have shown earlier the information channel that arises from dynamic learning. While W_1 increases linearly with m_1, W_2 is non-monotonic in m_1 and increases with m_2 in a non-linear manner. Because the government also faces a hard budget constraint $m_1+m_2=M$, an increase in m_1 necessarily crowds out m_2 through the budget channel (e.g., Geithner (2014, pp. 264–266) on intervention cost and budget consideration). When the government optimally allocates resources in two periods, it needs to consider both.

Fig. 4 plots a typical social welfare W as m_1 varies. Both the intuitions and the pattern are similar to those in Fig. 3.

The intuitions again depend on the comparison between the endogenous correlation effect and the conditional inference effect. The patterns delivered by the figure hold for all parameters. W is always flat for either small or large m_1. W always attains its maximum at $m_1 = \frac{M+c}{2}$. Therefore, whenever M is larger than c, the government should invest $m_1^* = \frac{M+c}{2}$. Lemma 5 in Online Appendix A summarizes the aggregate social welfare and the net benefit of initial intervention.

Proposition 5 characterizes the optimal intervention.

Proposition 5 (optimal intervention). *The optimal intervention under budget constraint M is* $\min\left(\frac{c+M}{2}, M\right)$. *Optimal intervention always emphasizes initial intervention: $m_1^* > m_2^*$.*

The optimal intervention plan depends on M, the total resources available to the government. When M is small ($M < \frac{M+c}{2}$), it is optimal to set $m_1 = M$. When M gets larger, setting $m_1 = M$ can be suboptimal, and the optimal initial intervention is $m_1 = \frac{M+c}{2}$.

At the optimal intervention level, the fund in period 2 survives if and only if the fund in period 1 survives. The endogenous correlation effect completely dominates. The intuition for $m_1^* > m_2^*$ is then apparent. Suppose the government equally splits the budget and invests $\frac{M}{2}$ in each period. Two periods' intervention outcomes are completely correlated. Knowing this, government always has incentives to kill two birds with one stone, that is, increasing m_1 to increase the survival probability in both funds. The ratio $\frac{m_2^*}{m_1^*}$ is weakly increasing in M and weakly decreasing in c. Thus, the tilt toward initial intervention is most significant when the government has a small budget or the illiquidity cost is high.

One can question whether the results are driven by the fact that imposing the budget constraint takes away the flexibility of m_2 after m_1 is chosen. By specifying a very general $K(m_1,\ m_2)$, we show that emphasizing initial intervention is a robust phenomenon under committed interventions.

Proposition 6 (emphasis on early intervention). *If the intervention cost satisfies* $K(m_1, m_2) > K\left(\frac{1}{2}[m_1 + m_2], \frac{1}{2}[m_1 + m_2 - 2c]\right)$, *the optimal policy strictly emphasizes initial intervention, that is, $m_1^* > m_2^*$.*

The condition in the proposition is satisfied by many plausible cost functions, such as one that is separable and symmetric in m_1 and m_2, or one that emphasizes consistency in the sense that $K(m_1,\ m_2)$ depends only on $m_1 + m_2$ and $|m_1 - m_2|$ and is increasing in $|m_1 - m_2|$. One natural example is $K(m_1, m_2) = k(m_1) + k(m_2)$. The $-2c$ in the condition derives from the endogenous correlation effect. If the first intervention optimally uses m, the second needs only $m - c$ because initial success makes later intervention easier to succeed due to positive updating and initial failure makes additional intervention futile due to negative updating.

Proposition 6 is not about comparing the absolute sizes of the interventions. Given that we have normalized the total capital in the economy to one in both periods, we are talking about a notion of intervention relative to the market size. Therefore, the conclusion could apply more broadly, especially when the coordination games are scale invariant, that is, the normalized intervention, cost, and participation scale proportionally with the market size.

4.2. Information externality and myopic intervention

This subsection examines the situations in which the decision maker for the initial intervention does not fully take into consideration the informational impact on subsequent interventions. This scenario happens when the incumbent government is not expecting to be reelected and thus does not consider the impact of current intervention on coordination and interventions under the future government. This scenario could also happen when one European Union country's intervention does not fully consider the informational externality on neighboring countries with correlated fundamentals.

To highlight the information externality from the initial intervention, we shut down the budget channel in our general intervention cost function by setting $K_{12}(m_1, m_2) = 0$ for the remainder of the paper. The case of a hard budget constraint trivially predicts that the more the government considers the welfare in the second period, the less it would intervene in the first period. For a given m_1, let

$$Y(m_1; \chi) = W_1 + \chi \max_{m_2} E[W_2] - K(m_1, m_2). \tag{14}$$

$Y(m_1;\ \chi)$ is the social welfare given the initial intervention m_1. The choice of m_2 is already optimized, and the government chooses m_1 to maximize the social welfare. Here, $\chi \in [0, 1]$ measures how much the government cares about the fate of the fund in the second period. $\chi = 0$ corresponds to the static benchmark, and $\chi = 1$ corresponds to the case in which the second fund's fate is equally important. $\chi < 1$ corresponds to the short-termism of the government. In the context of the global economy in which countries' fundamentals are correlated, χ captures the extent to which one country considers the externality it imposes on others.

We are interested in $\frac{\partial m_1^*}{\partial \chi}$, the effect of government myopia on the initial intervention. By Theorem 2.1 in Athey et al. (1998), $m_1^* \equiv \operatorname{argmax}_{m_1} Y(m_1, \chi)$ is nonincreasing in χ if and only if Y has decreasing differences in χ and m_1 and is nondecreasing in χ if and only if Y has increasing differences in χ and m_1.

Proposition 7 (myopic intervention). *A myopic government can under or over intervene initially. It*

1. *under intervenes* ($\frac{\partial m_1^*}{\partial \chi} \geq 0$) *if and only if either $m_1^* \geq c$ and $m_2^* = m_1^* - c$ always or $m_1^* \leq c$ and $m_2^* = 0$ always;*
2. *over intervenes* ($\frac{\partial m_1^*}{\partial \chi} \leq 0$) *if and only if either $m_2^* > m_1^* + 1 - c$ always or $m_1^* > c$ and $m_2^* < m_1^* - c$ always.*

Proposition 7 emphasizes m_1 relative to the case in which the intervention externality is absent. A myopic government under-intervenes initially when intervention outcomes are perfectly correlated. This scenario happens when the costs of intervention in the two periods are comparable. When they are both large ($m_1^* \leq c$ and $m_2^* = 0$) or both small ($m_1^* \geq c$ and $m_2^* = m_1^* - c$), the endogenous correlation effect dominates. Therefore, increasing the proba-

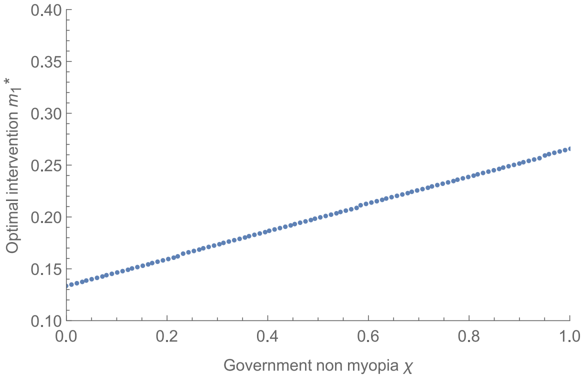

Fig. 5. m_1^* **as an increasing function of** χ. This figure plots the government's optimal initial intervention m_1^* as a function of χ, which measures to what extent policy maker considers the welfare in the subsequent period. In this case, the cost functions across two periods are comparable and the optimal initial intervention increases with χ. Parameters are $\delta = 1.2,\ c = 0.6,\ B = 3,\ k_1 = 0.5,\ k_2 = 0.5,$ and $K(m_1, m_2) = \frac{1}{2}k_1m_1^2 + \frac{1}{2}k_2m_2^2$.

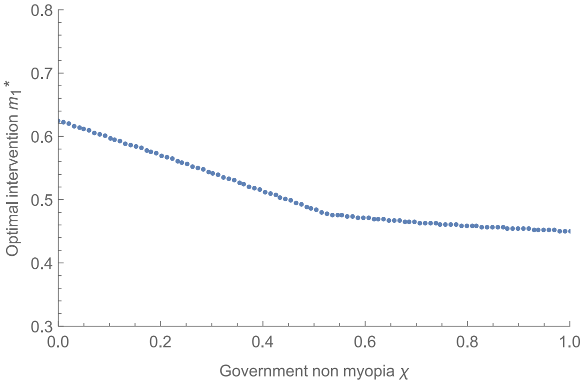

Fig. 6. m_1^* **as a decreasing function of** χ. This figure plots the government's optimal initial intervention m_1^* as a function of χ, which measures to what extent policy maker considers the welfare in the subsequent period. In this case, the cost functions across two periods are not comparable and the optimal initial intervention decreases with χ. Parameters are $\delta = 2,\ c = 0.25,\ B = 3,\ k_1 = 0.2,\ k_2 = 0.8,$ and $K(m_1, m_2) = \frac{1}{2}k_1m_1^2 + \frac{1}{2}k_2m_2^2$.

bility of survival by increasing m_1 also benefits investors in the second period, a fact that a myopic government neglects.

Failure to consider dynamic coordination could also result in excessive intervention. This happens when the cost for the first intervention is sufficiently small such that the initial intervention is large-scale, yet the second intervention is sufficiently costly that survival does not always lead to continued survival. Meanwhile, a high m_1 reduces the quality of good news, reducing the marginal benefit of m_2. When the costs of intervention in the two periods are disproportionate, outcomes are less correlated, and the conditional inference effect dominates. For a myopic government, shading m_1 makes intervention in the second period easier regardless of whether the fund survives or fails in the first period.

We illustrate the results in Figs. 5 and 6. More generally, without global increasing or decreasing differences, m_1^* can be non-monotonic in χ, as seen in Fig. 7. Furthermore, to link Proposition 7 to exogenous parameters, we

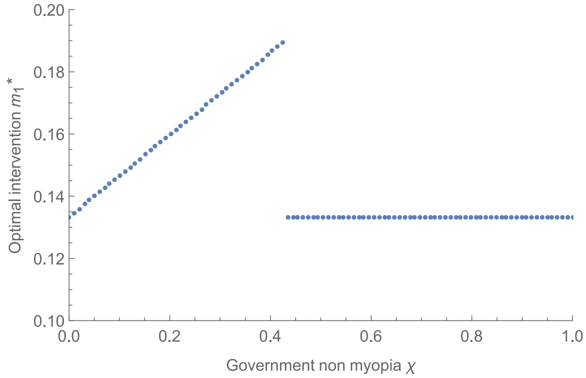

Fig. 7. m_1^* **as a non-monotonic function of** χ. This figure plots the government's optimal initial intervention as a function of χ, which measures to what extent policy maker considers the welfare in the subsequent period. In this case, the cost functions across two periods are not comparable and the optimal initial intervention is non-monotonic in χ. Parameters are $\delta = 1.2,\ c = 0.6,\ B = 3,\ k_1 = 0.5,\ k_2 = 0.01,$ and $K(m_1, m_2) = \frac{1}{2}k_1m_1^2 + \frac{1}{2}k_2m_2^2$.

provide some sufficient conditions in Online Appendix A for both under and over intervention.

Proposition 7 calls for coordinated interventions across governments. For example, because economic fundamentals across EU countries are highly correlated, one member's isolated intervention imposes informational externality on other members. In the case of AMLF and CPFF, because the capacity to intervene using CPFF is comparable to that in AMLF, the later intervention was likely able to capture the benefit from investors' learning of earlier intervention. Proposition 7 thus provides additional justification for the overwhelming scale of AMLF.

4.3. *Intervention with heterogeneous funds*

In this subsection, we consider how the government intervenes in two funds of different sizes, given the dynamic coordination effect. Our main results are two fold. First, the government tends to put more resources into the fund whose outcome is more likely to realize first, when cost function does not differ significantly across the interventions. This is essentially Propositions 5 and 6 extended to funds of heterogeneous size and stochastic realization of ordering. Second, it is optimal to provide more resources to the smaller fund that are disproportional to its size and the likelihood that its outcome is realized first. When the two funds are equally likely to have their outcomes realized, the government puts disproportionately more resources into the smaller one.

Without loss of generality, we normalize the size of fund 1 to 1 and the size of fund 2 to $\lambda > 1$. Here, size simply refers to the total measure of investors. We continue to assume that fund 1 survives if and only if

$$A_1 + m_1 \geq \theta, \tag{15}$$

where A_1, m_1, and θ have the same interpretations as before. In addition, fund 2 survives if and only if

$$\lambda A_2 + m_2 \geq \theta\lambda, \tag{16}$$

where $A_2 = \frac{\int_0^\lambda 1\{a_{2i}=1\}ds}{\lambda} \in [0,1]$ is the fraction of investors who choose to stay and, thus, λA_2 is the liquidity from remaining investors. Fund 2 survives if and only if the total liquidity is greater than $\theta\lambda$. The threshold is also augmented by λ, so that we are not distorting the funds' survival probability absent interventions.

θ in the baseline specification captures the systemic illiquidity for a market or fund of unit size. Therefore, we scale it up when the fund size scales up. This is a natural specification, because if we keep θ unscaled while changing the size of the fund, we are implicitly making a larger fund more likely to survive, which clouds the informational effect on which we hope to focus. To see this, let us examine the static example. The survival threshold for the larger fund becomes $\lambda(1-c)+m$, so, with the same intervention, the larger fund survives with greater probability.

Our analysis so far has assumed without loss of generality that fund 1's outcome is always realized before fund 2's, because these two funds are homogeneous. When two funds differ in size, it matters which fund has its outcome realized first. To proceed, we assume that, with probability $q \in (0, 1)$, fund 1's outcome is realized first and, with probability $1-q$, fund 2's outcome is realized first. Given this probability, the government chooses m_1 and m_2 to continue to maximize the total social welfare.

In the case in which the government has a budget constraint $m_1+m_2 = M$ and allocates resources proportional to fund size, then $m_1 = \frac{M}{1+\lambda}$ and $m_2 = \frac{M\lambda}{1+\lambda}$. Proposition 8 shows that the government puts relatively more resources into the fund whose outcome is more likely to realize first. When $q = \frac{1}{2}$ so that both funds' outcomes are equally likely, the government put more resources into the small fund.

Proposition 8. A government facing hard budget constraint $m_1+m_2 = M$ chooses the following optimal intervention policy.

1. *If $q > \frac{1}{\lambda+1}$, $m_1^* = \frac{M+c\lambda}{1+\lambda}$ and $m_2^* = \frac{(M-c)\lambda}{1+\lambda}$.*
2. *If $q < \frac{1}{\lambda+1}$, $m_1^* = \frac{M-c\lambda}{1+\lambda}$ and $m_2^* = \frac{(M+c)\lambda}{1+\lambda}$.*
3. *If $q = \frac{1}{\lambda+1}$, $m_1^* \in \left[\frac{M-c\lambda}{1+\lambda}, \frac{M+c\lambda}{1+\lambda}\right]$ and $m_2^* = M - m_1^*$.*

When $q = \frac{1}{2}$, $m_1^* = \frac{M+c\lambda}{1+\lambda} > \frac{M}{1+\lambda}$.

Online Appendix Section A.7 contains the proof. When $\frac{1}{\lambda+1} < \frac{1}{2}$, it means that even when the smaller fund is likely to realize its outcome later ($q \in (\frac{1}{\lambda+1}, \frac{1}{2})$) the government still favors disproportionally helping it more, for the following two reasons. First, given a probability to realize its outcome first, the smaller fund costs less intervention resources to generate the same informational environment. Second, the larger fund benefits more from the resolution of uncertainty due to the revelation of the initial intervention's outcome. These intuitions also imply that if the government can determine which fund realizes the outcome first, it would choose the smaller one first. The result carries through with general intervention cost functions with $K\left(m_1, \frac{m_2}{\lambda}\right) > K\left(\frac{1}{2}\left[m_1 + \frac{m_2}{\lambda}\right], \frac{1}{2}\left[m_1 + \frac{m_2}{\lambda} - 2c\right]\right)$, a slight modification from the condition in Proposition 6.

Our result thus relates to the concept of "too big to fail." Instead of emphasizing financial networks and connectedness, we are adding an information structure perspective to the debate on systemic fragility. Some institutions could be too big to fail, but the best way to save them could entail putting more resources into the smaller ones to better boost market confidence. Our results do not contradict the concept of "too big to fail" in that we are not discussing which institutions to save, but which institutions to save first. One way to think about this is that among the too big to fail institutions, if the government can commit to which institution's intervention outcome is to be revealed first, revealing the intervention outcome of the smaller fund first is informationally efficient.

5. Discussions and extensions

The economic intuition and main results in the paper are robust to a wide range of alternative specifications. In this section, we briefly discuss how imperfectly correlated fundamentals, contingent interventions, and alternative forms of interventions can be accommodated in our framework. In the Online Appendix, we further extend the model to incorporate general ranges of δ and c, θ dependent payoff structures, moral hazards, normally distributed signals, and general bounded noise distributions.

5.1. Imperfectly correlated fundamentals

So far, we have assumed $\theta_1 = \theta_2$. What if the fundamentals across the two periods are positively correlated but nonidentical? In this subsection, we introduce one tractable way to model this scenario.

Suppose, at the beginning of period 2, everyone learns whether the fundamental in period 2 is identical to that in period 1 or just an independent one: that is, whether period 2 is an extension of period 1's coordination game or an independent one becomes public. We assume that with probability π, $\theta_2 = \theta_1$, and with probability $1-\pi$, θ_2 is a random draw from $[-B, B]$ independent of θ_1. Our baseline model corresponds to $\pi = 1$. In the case in which $\pi = 0$, the intervention problem is symmetric, which yields our benchmark policy $m_1^* = m_2^*$. With $\pi \in (0, 1)$, the intuition for all the implications continues to apply and the previous results are affected only qualitatively. We can show that, similar to Proposition 7, the correlation positively increases m_1^* when the cost functions are comparable (Corollary 2 in Online Appendix Section A). The correlation reduces m_1^* if the cost functions are asymmetric (Corollary 3 in Online Appendix Section A). Otherwise, the effect could be non-monotone, as illustrated in Figs. 5–7 (replacing χ by q). Thus, how the correlation in the fundamental affects endogenous government intervention also depends on the intervention costs.

5.2. Contingent interventions

In reality, the government can sometimes choose the size of the later intervention after the outcome of the initial intervention is realized. We analyze this case in this subsection. Let $\{m_1, m_{2S}, m_{2F}\}$ be the government's intervention, where m_{2S} and m_{2F} are the second period's intervention upon $s_1 = S$ and $s_1 = F$. The intuition and key trade-off in earlier discussions still apply. Any $m_{2F} \in \left(0, 1 + m_1^* - c\right]$ cannot be optimal because if $s_1 = F$, the fund in the second period still fails for sure despite the costly intervention. Given this, if $m_{2F}^* = 0$, the endogenous correlation effect is even reinforced. If $m_{2F}^* > 1 + m_1^* - c$, it is possible to have failed initial intervention but successful subsequent intervention, and the endogenous correlation effect is weaker. Nevertheless, the overall dynamic coordination still boils down to a trade-off between the endogenous correlation effect and the conditional inference effect.

Intuitively, if the cost for the subsequent intervention (second period) increases with the amount of intervention m_2 fast enough relative to the first period, then $m_{2F}^* = 0$ because conditional on failure, it is not worthwhile to intervene more given the pessimistic posterior. Therefore, endogenous correlation dominates and initial intervention is emphasized, i.e., $m_1^* > m_{2S_1}^*$, due to the same reasoning as in Proposition 6.

With contingent interventions, the myopic government still under or over intervenes initially. If endogenous correlation effect dominates the conditional inference effect, the optimal initial intervention is weakly increasing in the extent it considers dynamic coordination, i.e., $\frac{\partial m_1^*}{\partial \chi} \geq 0$. Otherwise, it is weakly decreasing. When $m_{2F}^* = 0$, the endogenous correlation effect is the same as in the committed intervention case, and the same intuition carries through.

Finally, regarding the sequence of interventions in funds of different sizes, saving the smaller fund disproportionally more relative to its size and probability of realizing the coordination outcome first (and saving it first if the government can decide the order of the realizations) is still cheaper for creating the same informational environment, plus the larger fund still benefits more from the uncertainty reduction. A policy that induces perfectly correlated outcomes and saves the larger fund first or disproportionally more relative to its size cannot be optimal. In Online Appendix Section C, we discuss how the intuition in Propositions 6, 7, and 8 extends to the case of contingent interventions.

5.3. Various forms of interventions

In the model, we have interpreted intervention as liquidity injection. Our model captures a broader array of interventions that are commonly used (Bebchuk and Goldstein, 2011; Diamond and Rajan, 2011). Examples follow.

Direct lending and investing in borrower funds. This is exactly the interpretation in our model. During the financial crisis of 2008–2009, the US government directly participated in the commercial paper market through direct purchasing. Our general cost function to a large extent captures investment returns to the government and some inefficiencies discussed in Bebchuk and Goldstein (2011).

Direct capital infusion to investors. Governments around the globe have injected capital to both retail and institutional investors. For instance, the US Troubled Asset Relief Program provided about \$250 billion to banks, and the UK injected about \$90 billion to its major banks. Tax breaks and related measures represent capital infusion to retail investors directly. To map these policies into our model, suppose the government injects a fraction α of investors' existing capital. This changes the capital of each investor from 1 unit to $1+\alpha$ without altering the investor's optimization problem. Consequently, the one period survival threshold becomes $\theta^* = (1-c)(1+\alpha)$. We can relabel $m = (1-c)\alpha$ and the model solutions are equivalent.

Government guarantees. During the financial crisis, governments used guarantees that are similar to the Federal Deposit Insurance Corporation to limit the potential losses of the lenders. In our model, suppose that the government guarantees a proportion ξ of a lender's or investors' losses, then the lender who stays (rolls over) receives the return R if the fund survives and $-(1-\xi)c$ if it fails. Because our investors are risk-neutral, the survival threshold now is $\theta^* = \frac{1-c}{1-c\xi}$. We can relabel $m = \frac{c(1-c)\xi}{1-c\xi}$, which is equivalent to an intervention that increases the probability of success.

Interest rate reduction During the financial crisis, the Federal Reserve Board cut the federal funds rate from 4.25% in January 2008 to 1% in October 2008. Many other countries took similar measures in the face of a global contraction in lending. In the model, this is equivalent to reducing r, the payoff for not investing. Under risk neutrality, it is equivalent to increasing the survival probability through changing c, which is the role of m in our model.

6. Conclusion

How should a benevolent government choose policy for multiple interventions in a dynamic environment? Through the lens of sequential global games in which the government is a large player that mitigates coordination failures, we establish the existence of and characterize the equilibria, and we show that government interventions can affect coordination both contemporaneously and dynamically. A stronger initial intervention helps subsequent interventions through increasing the likelihood of positive news but also leads to negative conditional updates. Our results suggest that optimal intervention often emphasizes initial action, validating the conventional wisdom. However, depending on costs across interventions, an initial intervention could have either a positive or negative informational externality on subsequent coordination. Finally, some funds are too big to save first, because they benefit more from resolution of uncertainty about the fundamentals, and first intervening in smaller funds leads to lower cost to generate this informational structure. Our paper thus has policy relevance to various intervention programs, such as the bailouts of money market mutual funds and of the financial commercial papers market during the 2008 financial crisis.

The dynamic learning mechanism and thus the information structure effect also apply to broader contexts, such as interventions in currency attacks, credit market freezes, cross sector industrialization, regulatory union, and green energy development. Our discussion therefore opens several avenues for future research. For example, how does the government simultaneously design information structure and signal private knowledge about economic fundamentals? Moreover, this paper considers only common forms of interventions. Understanding the optimal contingent intervention not only is of theoretical interest, but also provides new insights and guidance to policy makers.

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