Coordination of Humanitarian Aid by Mediated Communication*

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Abstract. *We examine a setup where two agents allocate a fixed budget of aid between two equally needy areas. The agents may be biased to one area which is their private information. With no communication aid is allocated inefficiently. Direct communication between the agents in uninformative and cannot resolve the coordination failure. We show that a mediator who filters the information communicated by the agents and reveals it only partially can improve aid coordination.* (*JEL* Codes: D82, D83, H41, H84, L31)

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1 Introduction

Banerjee (2007) starts his book *Making Aid Work* with an episode from the 2005 earthquake in Pakistan. When international organizations and NGOs rushed in to help, a group of economists got concerned about how the aid would get to the right people. As no one was keeping track of where the aid had been delivered, some villages received many consignments while others had no aid. The economists figured out that coordination would be improved by a website to which everyone could report the location and amount of aid sent. Based on this information the organizations could decide where the next consignments should go. Disaster management information system Risepak was swiftly developed to achieve this goal.[1] Unfortunately the humanitarian organizations were largely not willing to share their information and Risepak did not reach a critical mass. The problem is not limited to this emergency but is a well-known phenomenon. For example, the coordination failure of the humanitarian response after the 2010 earthquake in Haiti has been attributed to a widespread unwillingness to share information (IASC 2010 and Altay and Labonte 2014).

We approach this allocation problem from the point of sensitivities in information sharing. As much as the humanitarian organizations aim to alleviate suffering, there is diversity in primary motivations and this diversity can hinder efficient information sharing. Non-neutrality of humanitarian aid is well established at the country level. In addition to needs, news coverage and bilateral relationship (e.g. colonial history, trade relationship, common language and geographic proximity) increase humanitarian aid (Drury et al. 2005, Eisensee and Strömberg 2007, Strömberg 2007 and Fink and Redaelli 2011). Some countries give more humanitarian aid to oil exporting countries (Fink and Redaelli 2011) while there is mixed evidence about political motivations (Drury et al. 2005, Strömberg 2007, Fink and Redaelli 2011 and Fuchs and Klann 2013). Furthermore, "new" donors' motivations differ from the OECD countries (Fuchs and Klann 2013). Regional biases are a less explored topic. Spatial inertia favours regions where the humanitarian organizations have prior operations (Jayne et al. 2002). Some governments target relief aid to regions with stronger political support (Jayne et al. 2001, Plümper and Neumayer 2009, Francken et al. 2012) or to more informed electorates (Besley and Burgess 2001, 2002). Furthermore, it is generally believed that NGOs locate to media hotspots as visibility and demonstrable activity are important for securing funding (Cooley and Ron 2002).

We examine a setup where two agents allocate a fixed budget of aid between two areas A and B. The areas are equally needy and therefore an equal allocation of aid would maximize social welfare. The agents may, however, have biased preferences which is their private information.[2] The agent is aligned with social welfare

[1] See Amin (2008) for more details about Risepak.

[2] Bias can be private information either because the types are unknown to other agents or

(neutral type) or biased to area A or B. With no communication aid is allocated inefficiently resulting in gaps and duplication in provision of aid. We show that direct communication between the agents cannot improve the allocation. The agent biased to area A would have an incentive to represent himself as the type biased to B in an attempt to get the other agent to allocate more aid to area A rendering communication uninformative.

We then introduce a mediator (or a coordinator or a leader) who communicates with the agents but does not have authority over them. The agents report their type (or, alternatively, their planned allocations[3]) to the mediator as cheap talk (i.e., costless and unverifiable messages *a la* Crawford and Sobel, 1982). The mediator can commit to a communication protocol which determines what information is revealed to the agents. The mediator reveals the types fully only if both agents report neutral. In this case, the mediator randomly assigns an area for each agent to specialize in. It is incentive compatible for the neutral type to follow the mediator's instruction as it results in an equal allocation of aid maximizing each agent's utility and the social welfare.

The mediator filters the rest of the information revealing only if both agents are biased or only one – but not the direction of the bias. Since the direction of the bias is not revealed, a biased agent cannot gain anything by representing himself as the opposite type. However, he might gain from reporting neutral. Randomization discourages the biased types from untruthfully reporting neutral. When an agent biased to area A is instructed to specialize in area B (after an untruthful report), he knows that the other agent will allocate all of his budget to A and he can obtain his preferred allocation by diverting some of his budget to A. However, when the instruction is to specialize in area A he knows that the other agent does not allocate anything to A and he cannot bias the total allocation in favour of area A.

We show that such information management reveals the agents' types truthfully and results in a more equal allocation of aid[4] if the bias to area A and B are of a relatively similar magnitude. We further analyze a modified communication protocol where the mediator gives a noisy instruction to specialize. Then mediated communication increases the expected social welfare even when the magnitudes of the bias diverge significantly.

The Humanitarian Reform of 2005 introduced Cluster Approach to improve coordination of humanitarian aid[5]. Cluster Approach divides the response to various

because there is uncertainty about which agents will enter a given emergency.

[3]In direct revelation mechanism the agents report their types. An equivalent indirect mechanism that matches more with the real world is where the agents report their planned allocations. The mediator then interprets equal allocation as neutral type and allocation in favour of A (resp. B) as the type biased to area A (resp. B).

[4]Strictly speaking, the allocation of aid is more equal for all but one type realization and the expected social welfare is higher.

[5]https://www.humanitarianresponse.info/en/about-clusters/what-is-the-cluster-approach

clusters, e.g. shelter, nutrition and health, and assigns a leader organization to coordinate each cluster. Although the cluster leads do not have authority over the partners participating in the clusters they, however, have means to induce coordination. One of such incentives is information sharing. Cluster Approach offers several information management tools, for example 'Who does What Where' (3W) and Humanitarian Dashboard. 3W reports which organizations are operating in which clusters and in which districts. However, the districts are large and there is no information about the budgets. Humanitarian Dashboard reports the percentage of aid requirements met in each cluster and has some geographical information. These tools help decision making but they lack geographic detail.

We propose that humanitarian organizations report their planned and actual response in geographic detail to the cluster lead who filters the information.[6] The first important feature of the communication protocol in our model is that it reveals information only partially.[7] The current information management tools may already do that. However, they lack geographic detail such as Risepak was trying to achieve. On the other hand, Risepak went too far in transparency. In its open access website, everyone could see the full activities of each (participating) humanitarian organization at a village level.[8] However, the system could be amended to filter the information so that the activities of individual organizations are not revealed. The data on overall geographic allocation of aid could be displayed on a map for clear visualization of the humanitarian response.[9]

The second important feature of our communication protocol is that the coordinator can give instructions to humanitarian organizations about where to deliver aid. Following the instructions is, however, voluntary for the organizations. The coordinator could even be an algorithm producing recommendations based on the previous response and the evolving needs.[10] This could be particularly beneficial for speeding up the early response at the time when the needs are most pressing.

In related work mediated communication has been analyzed by e.g. Goltsman et al. (2009) and Ivanov (2014). They analyze communication between an informed party and a decision maker while in our model there is two-sided asymmetric in-

[6] In related work in Operations Management, Altay and Pal (2014) analyze the role of cluster lead as information hub in an agent-based model. They find the information diffusion is faster when cluster lead acts as information hub and filters information. Their definition of filtering is passing relevant information and checking its reliability. In our model the role of filtering is strategic aiming to give the agents incentives to reveal their information.

[7] This can be a more general principle than the specific communication protocol examined in our model.

[8] Such open access website is equivalent to direct communication in our model.

[9] Recently developed Crisis Mapping technology crowdsources real-time reports about evolving crisis and displays the data on a map for clear visualization of the *needs* (Meier, 2015). Similar technology could also be used for visualizing the *delivery* of humanitarian aid.

[10] In our model the needs are given. Introducing dynamically evolving needs is an interesting direction for future research.

formation and both agents take an action. Hörner et al. (2015) analyze mediated communication in two-sided asymmetric information case but their focus is on splitting a pie which may shrink due to war. We examine two agents contributing to a public good. In Goltsman et al. (2009) and Hörner et al. (2015) the mediator recommends an action and the recommendation has the nature of both filtering information and adding noise. In our paper the mediator recommends an action only if both agents report neutral (in the modified protocol the recommendation is noisy). Otherwise the mediator filters information.

Direct communication between agents making voluntary contributions to a public good has been examined by Palfrey and Rosenthal (1991) and Palfrey et al. (2016). Their setup differs from ours in that there is only one public good and therefore a freeriding incentive arises. However, the public good is discrete and a threshold of contributions is needed giving the agents an incentive to coordinate. They obtain theoretical bounds on the gains from communication and show that direct communication can enhance efficiency. However, in experiments only unrestricted text chat – but not coarser forms of communication such as binary messages – improve efficiency.

Our work is also related to the literature on organizational design and communication such as Alonso et al. (2008) and Rantakari (2008). They analyze allocation of control rights within a hierarchy and its effect on vertical and horizontal communication within the firm. In our paper the agents are independent organizations and keep their control rights. Our focus is on the structure of external communication.

The paper is structured as follows. Section 2 sets up the allocation game. Section 3 examines the allocation game when the agents do not communicate. Section 4 shows that direct communication between the agents cannot improve upon the outcome of no communication. Section 5 examines mediated communication and derives the conditions under which it results in welfare improving allocation. Section 6 concludes.

2 Model

There are two agents, 1 and 2, with a budget of 1 to allocate in aid between two equally needy areas, A and B. Agent i allocates a_i to area A leaving $1 - a_i$ to area B.[11] The social welfare index is

$$w(a) = -(1-a)^2$$

where $a = a_1 + a_2$. Social welfare is maximized by allocating half of the total budget of 2 to area A.

[11] For expositional ease, we assume that the agents must allocate all their budgets. This is the case in equilibrium if both agents' utility functions increase in allocations to each area.

The agents may be biased toward one area. They are one of three types in $T := \{l, n, h\}$ and have a utility function $-(1 - a + t)^2$ when of type $t \in T$ where $l < n = 0 < h$. An l-type (h-type) is biased against (toward) area A and an n-type is unbiased. Agent's type is their private information. Note that, abusing notation slightly, l, n and h are used both for the types and the degree of biases.

We assume that the prior on types is uniform. To simplify exposition, we also assume that the potential biases are not too large and have different magnitudes.

Assumption 1. $0 < |l| < h < \frac{1}{8}$.

Although there is diversity in motivations of the humanitarian actors, it is realistic to assume that they are not too biased. Different magnitude of bias can result e.g. from the strength of the bilateral relationship. That the bias is larger for h than for l is innocuous.

We compare the agents' allocation decisions with no communication, direct communication between the agents and mediated communication. Our interest is finding out when mediated communication can improve social welfare.

3 No Communication

The game with no communication is a standard static Bayesian game where the agents simultaneously decide on a_i contingent on their type. We characterize the set of Bayesian Nash equilibria which are type-contingent strategy profiles that satisfy mutual best response property.

Let $a_i = (a_i^l, a_i^n, a_i^h)$ denote agent i's allocation strategy where a_i^t is the amount that agent i allocates to area A when its type is $t \in T$. The marginal utility of allocating a_i^t for agent i of type t is

$$2 \sum_{s \in T} \frac{1}{3} \left(1 - a_i^t - a_{-i}^s + t\right) \tag{1}$$

where a_{-i}^s is the allocation of the other agent when its type is s. Then her unconstrained optimum from the first order condition is

$$a_i^t = 1 + t - E(a_{-i}) \tag{2}$$

where $E(a_{-i}) = \sum_{s \in T} \frac{1}{3} a_{-i}^s$ is the expected allocation of the other agent. Hence, a strategy profile (a_1, a_2) constitutes a Bayesian Nash equilibrium if it satisfies the unconstrained optimum condition (2) for all $i \in \{1, 2\}$ and $t \in T$. That is, it is an equilibrium as long as each agent of every type can adjust her allocation so that the expected allocation is equal to her ideal allocation, $1 + t$.

In such an equilibrium, $a_i^t = a_i^n + t$ for $t \in \{l, h\}$, so (2) is equivalent to

$$a_i^n = 1 - a_{-i}^n - \frac{h+l}{3},\ i = 1,2 \quad \Longleftrightarrow \quad a_1^n + a_2^n = 1 - \frac{h+l}{3}$$

provided that $|l| \leq a_1^n, a_2^n \leq 1 - h$ so that we have an interior equilibrium. In a symmetric equilibrium $a_1^n = a_2^n = 0.5 - (h+l)/6$. Additionally, there is a continuum of asymmetric equilibria which can be obtained by increasing agent i's allocation and decreasing agent $-i$'s allocation by the same amount as long as a_1^n and a_2^n remain in the interval $[|l|, 1-h]$. In all these equilibria, the total allocation is the same for any type realization and it is presented in Table 1 below. The allocation is inefficient, i.e., it diverges from the socially optimal allocation of 1 in every realization.

1\ 2	l	n	h
l	$1 - h/3 + 5l/3$	$1 - h/3 + 2l/3$	$1 + 2(h + l)/3$
n	$1 - h/3 + 2l/3$	$1 - (h + l)/3$	$1 + 2h/3 - l/3$
h	$1 + 2(h + l)/3$	$1 + 2h/3 - l/3$	$1 + 5h/3 - l/3$.

Table 1: Allocation with no communication

Note that we have only considered pure allocation strategies. As it is straightforward from the utility function that the unconstrained optimum a_i^t satisfies (2) even if the other agent adopts mixed strategies, it follows that no mixed strategy equilibrium exists. In addition, it can be shown that corner solutions are not viable in equilibrium. Thus, the result in the absence of communication is characterized as below.

Proposition 1 *In the absence of communication, the set of Bayesian Nash equilibria (a_1, a_2) is fully characterized by*
(i) $a_1^n + a_2^n = 1 - (h + l)/3$,
(ii) $|l| \leq a_1^n, a_2^n \leq 1 - h$, and
(iii) $a_i^t = a_i^n + t$ for $i \in \{1, 2\}$ and $t \in \{l, h\}$.
In all these equilibria, the total allocation to area A for each type realization is given in Table 1. The allocation is inefficient and the equilibrium payoff of each type is $-2(h^2 - hl + l^2)/9$.

Proof. It remains to show that in any equilibrium, $a_i^t \in [0, 1]$ is the unconstrained optimum, i.e., satisfies (2). Note that this is always the case for a_i^n because $E(a_{-i}) \in [0, 1]$. To prove by contradiction, assume that this is not the case for type l, i.e., $1 + l - E(a_{-i}) < 0$. Then, the constrained optimum value is $a_i^l = 0$ and accordingly, $E(a_i) = (2a_i^n + h)/3$ so that $a_{-i}^n = 1 - E(a_i) = 1 - (2a_i^n + h)/3 > 1 - h$ where the inequality holds due to $a_i^n < |l| < h$. This in turn would imply that the constrained optimum for agent $-i$ of type h is 1, so that $E(a_{-i}) = a_{-i}^n + (1 - a_{-i}^n + l)/3$ and consequently, $a_i^n = 1 - E(a_{-i}) = 1 - (1 + 2a_{-i}^n + l)/3 = (2 - 2a_{-i}^n - l)/3$. Together with

$a_{-i}^n = 1 - (2a_i^n + h)/3$ deduced above, this would dictate that $a_i^n = (2h - 3l)/5 > |l|$, contradicting the supposition that $a_i^n + l < 0$. It can also be shown analogously that a_i^h is the unconstrained optimum in every equilibrium.

Lastly, the expected payoff for l-type in equilibrium is one-third of

$$-\left[(1+l) - \left(1 - \frac{h}{3} + \frac{5l}{3}\right)\right]^2 - \left[(1+l) - \left(1 - \frac{h}{3} + \frac{2l}{3}\right)\right]^2 - \left[(1+l) - \left(1 + \frac{2h}{3} + \frac{2l}{3}\right)\right]^2$$

which is simplified to $-2(h^2 - hl + l^2)/9$. The optimization problem (1) is identical for all types when the control variable is redefined as $x = a - t$, and achieves the unconstrained optimum. Hence, all types obtain the same equilibrium payoff. ■

4 Direct communication

In this section, we study the case that the two agents communicate directly prior to making allocation decisions. We assume one round of simultaneous communication in which agents 1 and 2 send cheap talk messages to each other. In a Perfect Bayesian equilibrium (PBE), the agents update their beliefs about the other agent's type after receiving the message. Thus, associated with any message pair $(m_1, m_2) \in M_1 \times M_2$ are Bayes-updated posterior beliefs $\mu_i = (\mu_i^l, \mu_i^n, \mu_i^h)$ on agent i's type held by the other agent for $i = 1, 2$, where M_i is a finite set of messages used by agent i in the PBE. The dependence of μ_i on messages is suppressed when no confusion arises.

4.1 Allocations after communication

We first examine the allocation decisions after communication. The agents have updated their posterior beliefs to (μ_1, μ_2) and choose their allocations given their beliefs. Denoting the equilibrium allocations as (a_1^l, a_1^n, a_1^h) and (a_2^l, a_2^n, a_2^h), agent 1 of type $t_1 \in \{l, n, h\}$ solves

$$\max_{a_1^{t_1}} \; -\mu_2^l \left(1 - a_1^{t_1} - a_2^l + t_1\right)^2 - \mu_2^n \left(1 - a_1^{t_1} - a_2^n + t_1\right)^2 - \mu_2^h \left(1 - a_1^{t_1} - a_2^h + t_1\right)^2. \tag{3}$$

The first order condition is

$$2 \sum_{t_2 \in T} \mu_2^{t_2} \left(1 - a_1^{t_1} - a_2^{t_2} + t_1\right) = 0, \tag{4}$$

the solution of which is written out for each $t_1 \in T$ as

$$\begin{aligned}
a_1^l &: \mu_2^l \left(1 - a_1^l - a_2^l + l\right) + \mu_2^n \left(1 - a_1^l - a_2^n + l\right) + \mu_2^h \left(1 - a_1^l - a_2^h + l\right) = 0 \\
a_1^n &: \mu_2^l \left(1 - a_1^n - a_2^l\right) + \mu_2^n \left(1 - a_1^n - a_2^n\right) + \mu_2^h \left(1 - a_1^n - a_2^h\right) = 0 \\
a_1^h &: \mu_2^l \left(1 - a_1^h - a_2^l + h\right) + \mu_2^n \left(1 - a_1^h - a_2^n + h\right) + \mu_2^h \left(1 - a_1^h - a_2^h + h\right) = 0
\end{aligned}$$

Solving the equations subject to $0 \leq a_1^{t_1} \leq 1$ and by symmetry, we deduce that (a_1^l, a_1^n, a_1^h) and (a_2^l, a_2^n, a_2^h) constitutes an equilibrium if and only if they solve

$$\begin{cases} a_1^l &= \max\{0, 1+l-E(a_2)\} \\ a_1^n &= 1-E(a_2) \\ a_1^h &= \min\{1+h-E(a_2), 1\} \end{cases} \quad \text{and} \quad \begin{cases} a_2^l &= \max\{0, 1+l-E(a_1)\} \\ a_2^n &= 1-E(a_1) \\ a_2^h &= \min\{1+h-E(a_1), 1\} \end{cases} \tag{5}$$

Note that this is the case even when some μ_i does not have a full support, in which case $a_i^{t_i}$ is said to be "relevant" if $\mu_i^{t_i} > 0$ and "irrelevant" otherwise. To help exposition, we keep the values of irrelevant equilibrium variables according to (5).

<u>Interior equilibria</u>

We say that an equilibrium is *interior* if each relevant $a_i^{t_i}$ satisfies the first order condition (4). Consider an interior solution (a_1, a_2) to (5) under (μ_1, μ_2). Then, by taking expectation of a_1 and a_2 in (5) and rearranging, we get

$$E(a_1) + E(a_2) = 1 + h\mu_1^h + l\mu_1^l = 1 + h\mu_2^h + l\mu_2^l \tag{6}$$

$$\Longrightarrow \qquad h\mu_1^h + l\mu_1^l = h\mu_2^h + l\mu_2^l. \tag{7}$$

Thus, (7) is necessary for an interior equilibrium to exist, which means that the expected biases of the two agents are the same.

This condition can be understood as follows. Suppose agent 1 of type n chooses an allocation $a_1^n = 0.5$. Then the biased types of agent 1 choose $a_1^t = 0.5 + t$ for $t = l, h$. Then, expecting $E(a_1) = 0.5 + h\mu_1^h + l\mu_1^l$, Agent 2 of type n chooses her allocation so that the expected allocation equals her ideal allocation of 1, thus $a_2^n = 1 - E(a_1) = 0.5 - h\mu_1^h - l\mu_1^l$. Accordingly, the biased types of agent 2 choose $a_2^t = 0.5 - h\mu_1^h - l\mu_1^l + t$ for $t = l, h$. Therefore, agent 1 expects $E(a_2) = 0.5 - h\mu_1^h - l\mu_1^l + h\mu_2^h + l\mu_2^l$ and thus, $a_1^n = 0.5$ is an equilibrium if and only if $h\mu_1^h + l\mu_1^l = h\mu_2^h + l\mu_2^l$. By a similar argument, it continues to be an equilibrium when one agent increases her allocation and the other decreases his allocation by the same amount as long as all relevant variables $a_i^{t_i}$ are interior solutions, i.e, satisfy $a_i^{t_i} = 1 + t_i - E(a_{-i})$. Consequently, there is a continuum of equilibria all resulting in the same total allocation, $a_1^{t_1} + a_2^{t_2} = a_1^n + t_1 + a_2^n + t_2 = 1 - h\mu^h - l\mu^l + t_1 + t_2$, for each type pair (t_1, t_2) that may realize with a positive probability.

Note that (7) has been shown to be both necessary and sufficient for an interior equilibrium to exist in a continuation game with posterior beliefs (μ_1, μ_2). Moreover, suppose there is a non-interior equilibrium (a_1, a_2), say one relevant allocation of agent 1 does not satisfy (4), i.e, either $a_1^l = 0 > 1 + l - E(a_2)$ or $a_1^h = 1 < 1 + h - E(a_2)$. In the former case, $a_2^l = 1 + \ell - E(a_1)$ and thus, from (5) we deduce that $E(a_1) + E(a_2) > 1 + h\mu_1^h + l\mu_1^l$ while $E(a_2) + E(a_1) \leq 1 + h\mu_2^h + l\mu_2^l$, violating (7); in the latter case, (7) is also violated by an analogous reasoning. Therefore, the result on interior equilibria is summarized as

Lemma 2 *A continuation game with posterior beliefs* (μ_1, μ_2) *has only interior equilibrium if and only if (7) holds, or equivalently,*

$$E(\alpha|\mu_1) = E(\alpha|\mu_2) \quad \textit{where} \quad \alpha = (\alpha^l, \alpha^n, \alpha^h) = (0.5 + l, 0.5, 0.5 + h). \tag{8}$$

The set of equilibria (a_1, a_2) *in the continuation game is fully characterized by*

(i) $a_1^n + a_2^n = 1 - h\mu^h - l\mu^l$ *where* $h\mu^h + l\mu^l = h\mu_1^h + l\mu_1^l = h\mu_2^h + l\mu_2^l$,

(ii) $a_i^t = a_i^n + t$ *if* $\mu_i^t > 0$ *for* $i \in \{1, 2\}$ *and* $t \in \{h, l\}$.

In all these equilibria, the total allocation to area A conditional on type realization (t_1, t_2) *is as in Table 2 below so long as* $\mu_1(t_1) \cdot \mu_2(t_2) > 0$.

$1 \backslash 2$	l	n	h
l	$1 + 2l - h\mu^h - l\mu^l$	$1 + l - h\mu^h - l\mu^l$	$1 + h + l - h\mu^h - l\mu^l$
n	$1 + l - h\mu^h - l\mu^l$	$1 - h\mu^h - l\mu^l$	$1 + h - h\mu^h - l\mu^l$
h	$1 + h + l - h\mu^h - l\mu^l$	$1 + h - h\mu^h - l\mu^l$	$1 + 2h - h\mu^h - l\mu^l$

Table 2: Allocation with direct communication

<u>**Non-interior equilibria**</u>

Suppose (8) is not satisfied, say without loss of generality,

$$E(\alpha|\mu_1) \ < \ E(\alpha|\mu_2). \tag{9}$$

There is no interior equilibrium by Lemma 2. To understand this result suppose again that agent 1 of type n chooses allocation 0.5. Agent 2 would respond to it as above. However, now agent 1 expects $E(a_2) = 0.5 - h\mu_1^h - l\mu_1^l + h\mu_2^h + l\mu_2^l > 0.5$. Therefore $a_1^n = 0.5$ is not an equilibrium but agent 1's best response is $a_1^n < 0.5$. Then, to best respond to each other, agent 2 keeps increasing his allocation and agent 1 keeps reducing her allocation until agent 1 of type l or agent 2 of type h (or both) reach the boundary. This anchors the non-interior equilibrium to be unique. In any such equilibrium $a_1^n < a_2^n$ and a_1^h and a_2^l, as well as a_1^n and a_2^n, are interior.

Lemma 3 *If (9) holds, there is a unique equilibrium* (a_1, a_2) *and it is non-interior. Moreover,* $a_1^n < a_2^n$ *and* a_1^n, a_2^n, a_1^h *and* a_2^l *are interior solutions (even if irrelevant), i.e., they are characterized by the first order condition (4).*

Proof. If (9) holds, any equilibrium (a_1, a_2) must be non-interior by Lemma 2. As $1 - E(a_i|\mu_i) \in [0, 1]$, we deduce that a_i^n is an interior solution (even if irrelevant).

To show that a_1^h is interior, suppose otherwise, i.e., that $a_1^h = 1 < 1 + h - E(a_2|\mu_2)$, so that $E(a_1|\mu_1) < E(\alpha|\mu_1) + 1/2 - E(a_2|\mu_2)$. If a_2 is interior for relevant variables, then from (5) we have

$$E(a_2|\mu_2) = E(\alpha|\mu_2) + 1/2 - E(a_1|\mu_1) > E(\alpha|\mu_2) + 1/2 - E(\alpha|\mu_1) - 1/2 + E(a_2|\mu_2)$$

so that $E(\alpha|\mu_1) > E(\alpha|\mu_2)$, contradicting (9). If a_2 is not interior for relevant variables, then $a_2^l > 1+l-E(a_1|\mu_1)$ and thus, the equality in the displayed expression changes to ">" and the same contradiction results. By symmetric arguments, a_2^l is interior.

To show $a_1^n < a_2^n$, observe that $a_1^n \geq a_2^n$ would imply that a_1^l and a_2^h must be interior because otherwise, say if $a_1^l < 0$, then we would have $a_2^n \leq a_1^n < |l|$, contradicting $a_1^n = 1 - E(a_2)$. But, this would mean that the equilibrium is interior, contradicting Lemma 2. This establishes $a_1^n < a_2^n$.

To show existence and uniqueness, for $a^n \in [0,1]$ define $E_1(a^n) = \mu_1^l \max\{0, a^n - l\} + \mu_1^n a^n + \mu_1^h \min\{1, a^n + h\}$, then $b^n = 1 - E_1(a^n)$ and $E_2(b^n) = \mu_2^l \max\{0, b^n - l\} + \mu_2^n b^n + \mu_2^h \min\{1, b^n + h\}$ and finally $\psi : [0,1] \to [0,1]$ as $\psi(a^n) := 1 - E_2(1 - E_1(a^n))$. Note that the equilibrium a_1^n is a fixed point of ψ which is a continuously increasing function on a compact domain. By Brouwer's Fixed Point Theorem, ψ has a fixed point. Moreover, the derivative of ψ exists almost everywhere and is no higher than 1 (because so are E_1 and E_2). Therefore, if there were two equilibria, corresponding to say a^n and $\tilde{a}^n > a^n$, then $\psi'(a) = 1$ would have to hold for all $a \in (a^n, \tilde{a}^n)$, which would be possible only if the derivative of $E_1(a)$ is 1 for all $a \in (a^n, \tilde{a}^n)$ and also the derivative of $E_2(b)$ is 1 for all $b \in (1 - E_1(\tilde{a}^n), 1 - E_1(a^n))$, which in turn would imply that the two equilibria corresponding to a^n and $\tilde{a}^n$ (and a continuum of equilibria in between as well) are interior, contradicting Lemma 2. This establishes uniqueness of equilibrium and completes the proof. ■

4.2 Direct communication has no effect

Having examined the allocation choices, consider a PBE of the direct communication game in which $M_i = \{m_i^1, m_i^2, \cdots, m_i^{K_i}\}$ is the set of messages sent by agent i with positive probability. The associated posteriors are $\mu_i^1, \mu_i^2, \cdots, \mu_i^{K_i}$ for $i = 1, 2$. Without loss of generality, assume

$$E(\alpha|\mu_i^1) \leq E(\alpha|\mu_i^2) \leq \cdots \leq E(\alpha|\mu_i^{K_i}) \quad \text{and} \quad E(\alpha|\mu_1^1) \leq E(\alpha|\mu_2^1),$$

that is, the messages are ordered so that a higher message leads to a weakly higher expected bias, and label the agent with the lowest post-message expected bias as agent 1.

First, consider the case that $E(\alpha|\mu_1^{K_1}) \geq E(\alpha|\mu_2^{K_2})$ so that $E(\alpha|\mu_1^1) \leq E(\alpha|\mu_i^k) \leq E(\alpha|\mu_1^{K_1})$ for any $1 \leq k \leq K_i$ and $i \in \{1, 2\}$, i.e., the range of agent 1's expected bias is weakly wider than that of agent 2.

If $E(\alpha|\mu_1^1) = E(\alpha|\mu_1^{K_1})$, then the expected bias does not depend on the message or the agent and it must equal $(h + l)/3$. Consequently, by Lemma 2 the total allocation is the same as that without communication.

If $E(\alpha|\mu_1^1) < E(\alpha|\mu_1^{K_1})$, however, agent 1 would appear more likely to be of an h-type by sending the message $m_1^{K_1}$ than m_1^1, potentially steering the other agent's allocation toward the area B. In the Appendix we prove that type l has a greater incentive to send $m_1^{K_1}$ than the other types and thus, $E(\alpha|\mu_1^1) < E(\alpha|\mu_1^{K_1})$ is not viable in equilibrium. Consequently, $E(\alpha|\mu_1^1) = E(\alpha|\mu_1^{K_1})$ must hold and as above, the equilibrium allocation is the same as that without communication.

A key insight in this argument is that an l-type agent would have an incentive to pretend to be of an h-type in order to increase the other agent's allocation to his preferred area, and vice versa, rendering communication uninformative and ineffective. By the same insight, we prove in Appendix that the alternative case of $E(\alpha|\mu_1^{K_1}) < E(\alpha|\mu_2^{K_2})$ is not viable in equilibrium, either.

Proposition 4 *In every PBE of the allocation game preceded by one round of direct communication, the total allocation is identical to that in the equilibrium without communication.*

Proof. In Appendix ■

5 Mediated communication

We now consider mediated communication between the agents. In the first stage, the agents send privately a cheap talk message to the mediator (M). In the second stage, the mediator sends privately an "instruction" (which is also cheap talk) to each agent. The mediator does not have authority over the agents, so they are not obliged to follow the instructions. In the third stage, each agent simultaneously selects allocations contingent on his type, the message sent and the instruction received.

Before the first stage, the mediator can publicly and credibly commit to a communication protocol. Given the protocol, we examine the PBE of the continuation game between the two agents. Note that the Revelation Principle applies *à la* Myerson (1982) and thus, we only need to consider PBE's in which the agents report their types truthfully (by cheap talk messages) and follow the instruction received subsequently. Our aim is to show that mediated communication via a relatively simple protocol can improve social welfare (rather than identifying the optimal protocol). We start with the protocol described below and modify it later.

<u>Protocol P:</u>

- Each agent i may "report" or send a message $m_i \in \{l, n, h\}$ to M simultaneously as cheap talk.
- If $(m_1, m_2) = (n, n)$ is reported, then M instructs the agents to specialize (S) in a different area, i.e., agent 1 in A and 2 in B or vice versa, with equal probabilities.

- If $(m_1, m_2) \in \{l, h\} \times \{l, h\}$ is reported, both agents are instructed that there are two biased agents (B2).
- For all other reports (m_1, m_2), i.e., consisting of one n and one other message from $\{l, h\}$, both agents are instructed that there is one biased agent (B1).

It does not matter whether the instruction is done privately or publicly.

The babbling equilibrium is a PBE in any protocol: the agents mix all three messages equally regardless of their types, so that neither the messages nor the instructions carry any information and consequently, the agents choose allocations solely based on their types.

We say that Protocol P has a *mediated equilibrium* if there is a PBE of this game in which both agents report their types truthfully and follow the instruction S if received and play a continuation equilibrium described below if B2 or B1 is instructed.

5.1 Continuation game after communication

We start by assuming that the agents report truthfully and check the incentive compatibility later.

After S, upon being instructed to specialize in A or B, the agent infers with certainty that the other agent is also of n-type and is instructed to specialize in the other area. Following instructed specialization is clearly optimal for both agents.

After B2 is instructed, the agent (who is of l or h-type) knows that the other agent is equally likely to be of l or h-type and is instructed B2 as well. The expected bias equals $\frac{1}{2}(l + h)$ for both agents and therefore by Lemma 2 the continuation game has interior equilibria. The equilibria are characterized by Lemma 2 where $\mu^h = \mu^l = 0.5$. Any of these equilibria may be played in the continuation game after B2. In all these equilibria, the total allocation to area A conditional on type realization is as in Table 2.

Finally, consider the continuation game after B1 is instructed to both agents. In this game, a biased agent, say agent i, knows that her opponent is of type n. Therefore $E(\alpha|\mu_j) = 0.5$. Agent j of type n knows that the other agent is equally likely to be type l or h and therefore $E(\alpha|\mu_i) = 0.5\,(1 + l + h) > 0.5$. Accordingly, by Lemma 3 the continuation game has a unique non-interior equilibrium where $a_i^h = 1$.[12] The equilibrium is characterized by

$$a_i^n = 1 - a_j^n, \quad a_j^n = 1 - (a_i^n + l + 1)/2, \quad a_i^l = a_i^n + l, \quad a_i^h = 1.$$

Solving this equation system, we get

$$a_j^n = -l = |l|, \quad a_i^l = 1 + 2l, \quad a_i^h = 1.$$

[12] According to Lemma 3 a_i^h or/and a_j^l is non-interior if $E(\alpha|\mu_j) < E(\alpha|\mu_i)$. In this continuation game a_j^l is irrelevant.

Summarizing the analysis so far, the total allocation under the Protocol P is as below:

1\ 2	l	n	h
l	$1-h/2+3l/2$	$1+l$	$1+h/2+l/2$
n	$1+l$	1	$1-l$
h	$1+h/2+l/2$	$1-l$	$1+3h/2-l/2.$

Table 3: Allocation with mediated communication via Protocol P

On the other hand, the allocation with no or direct communication is as in Table 1.

The Protocol P achieves the welfare maximizing allocation 1 for type pair (n, n) as the agents specialize in different areas. When only one of the agents is of n-type, and instruction B1 is given, the allocation is closer to 1 than with direct communication. Finally, when both agents are biased, and instruction B2 is given, mediation increases welfare for all type pairs except (l, l). The next lemma shows that the welfare gain in (h, h) alone outweighs the lower welfare in (l, l).

Lemma 5 *The expected social welfare under the Protocol P conditional on truth-telling, is higher than that under babbling.*

Proof. Tables 1 and 3 show that the Protocol increases welfare for all type pairs except (l, l). It is easy to show that the welfare gain in the event (h, h) outweighs the welfare loss in the event (l, l) as below:

$$\frac{1}{9}\left[-\left(\frac{3h-l}{2}\right)^2+\left(\frac{5h-l}{3}\right)^2-\left(\frac{h-3l}{2}\right)^2+\left(\frac{h-5l}{3}\right)^2\right] = \frac{7\,(h+l)^2}{9\times 18}>0. \quad \blacksquare$$

5.2 When is truth-telling incentive compatible?

Given the continuation equilibrium under the Protocol P as in Section 5.1, we now examine if truth-telling is optimal for each type.

Suppose an l-type agent, say agent i, reports l truthfully. If her opponent, agent j, is of n-type, the mediator instructs B1 and agent i knows that her opponent is of n-type and will choose $a_j^n = -l$. Then agent i chooses $a_i^l = 1+2l$ to achieve her ideal total allocation $1+l$. If her opponent is of l or h-type, instruction B2 is given and the total allocation will be $1-h/2+3l/2$ or $1+h/2+l/2$ respectively as in Table 3. Therefore, an l-type agent's expected payoff from reporting l truthfully is

$$\frac{1}{3}\left\{-\left[(1+l)-\left(1-\frac{h}{2}+\frac{3l}{2}\right)\right]^2-\left[(1+l)-\left(1+\frac{h}{2}+\frac{l}{2}\right)\right]^2\right\}=\frac{-(h-l)^2}{6} \tag{10}$$

There is no incentive to report h untruthfully as the biased types are treated equally in the protocol.

Now suppose that type l reports n untruthfully. If her opponent is of n-type, S is instructed and with probability 1/2 she is directed to specialize in area A. She will instead allocate $1 + l$ to area A achieving her ideal allocation. However, with probability 1/2 she is instructed to specialize in area B while the opponent specializes in area A resulting in total allocation of 1. If her opponent is of n-type, therefore, l-type would be better off by reporting truthfully and obtaining her ideal allocation for sure. If her opponent is of type l or h, $B1$ is instructed. Then she anticipates that her opponent will take $a_j^l = 1 + 2l$ or $a_j^h = 1$ and *on average* she can obtain her ideal allocation $1 + l$ by allocating nothing to area A. In both cases, the total allocation is then l away from her ideal. By reporting truthfully, the total allocation would be further away, by $(l - h)/2$, from her ideal. Her expected payoff from reporting n untruthfully is

$$\frac{1}{3}\left\{-\left[(1+l)-(1+2l)\right]^2-\left[(1+l)-1\right]^2-\frac{1}{2}\left[(1+l)-1\right]^2\right\}=\frac{-5l^2}{6}. \qquad (11)$$

The benefit of truth-telling for an l-type agent is that she can obtain her ideal allocation if her opponent is of n-type. The cost of truth-telling is that the divergence from l's ideal allocation could be reduced from $(l-h)/2$ to l in case her opponent is of type l or h. The cost of truth-telling is low if the absolute values of l and h are of a relatively similar magnitude. According to equations (10) and (11) truth-telling is optimal for an l-type agent if and only if $l \leq -(1+\sqrt{5})h/4$.

Analogously, the expected payoff of an h-type agent from reporting h truthfully (or reporting l) is

$$\frac{1}{3}\left\{-\left[(1+h)-\left(1+\frac{h}{2}+\frac{l}{2}\right)\right]^2-\left[(1+h)-\left(1+\frac{3h}{2}-\frac{l}{2}\right)\right]^2-\left[(1+h)-(1-l)\right]^2\right\}$$
$$=\frac{-2(h+l)^2-(h-l)^2}{6}.$$

If she reports n untruthfully, her optimal allocation in case $B1$ is instructed is $h-l$ as she can on average obtain her ideal allocation $1+h$. Her expected payoff is

$$\frac{1}{3}\left\{-\left[(1+h)-(1+2l+h-l)\right]^2-\left[(1+h)-(1+h-l)\right]^2-\frac{1}{2}\left[(1+h)-1\right]^2\right\}=\frac{-h^2-4l^2}{6}.$$

The cost of truth-telling is the same as for l-type: she could reduce the divergence from her ideal allocation from $(l-h)/2$ to l by misreporting her type in case her opponent is of type l or h. The benefit of truth-telling is different: in case her opponent is of type n, the allocation is $h+l$ away from h's ideal when she reports her type truthfully and $\frac{1}{2}h$ away if she misreports. Therefore also the benefit of truth-telling is the higher, the closer l and h are in absolute value. That is why the incentive compatibility constraint for h-type, $l \leq (1-\sqrt{3})h$, is not binding. Note that $-0.81 < -(1+\sqrt{5})/4 < 1-\sqrt{3}$.

Finally, the expected payoff of an n-type agent from reporting truthfully is $-2l^2/3$. If she reports untruthfully and her opponent is of n-type, B1 will be instructed. Her opponent would allocate $-l$ to area A and she would equalize the resources by allocating $1 + l$, obtaining her ideal allocation which she could also achieve by reporting truthfully if her opponent is of n-type. When the opponent is of h or l type, an untruthful report by an n-type agent would lead to instruction $B2$. Her opponent's allocation to A when instructed $B2$ would be $h - l$ higher if of an h-type than if of an l-type and thus, her optimal response is to allocate so that the total allocation is $(h - l)/2$ away from 1 in either direction depending on the opponent's type. On the other hand, by truthful reporting the allocation is only l away from her ideal. Thus, her expected payoff from reporting untruthfully is $-(h - l)^2/6$ and it is straightforward to verify that truth-telling is always optimal for an n-type.

Proposition 6 *Protocol P constitutes a mediated equilibrium if and only if* $l \leq -(1 + \sqrt{5})h/4$. *Social welfare is higher in the mediated equilibrium than under the babbling equilibrium.*

The core insights behind welfare improvement under Protocol P are as follows. First, compared with the babbling equilibrium, the specialization (S) when both are of n-type improves welfare by implementing social optimum. For this effect to be sustainable, other types should be discouraged from reporting n untruthfully. This is why we introduce randomization of who specializes in which area. Then, h-type would suffer from under-allocation if she gets instructed to specialize in area A if her opponent is of n-type because the other agent would allocate nothing to area A.

However, just separating out the case that both agents are unbiased does not work. This is because in the continuation game when the agents are not instructed S (so that they only know that the report is different from (n, n)), an n-type would act differently from what she would in a babbling equilibrium because her posterior is concentrated on l and h. The allocation would vary more widely depending on the realized type pairs and overshadow the positive welfare effect of S.

The second element of Protocol P is separating out the cases where both agents are biased, B2. This has two effects. One is that it reduces the risk in the agent's posterior under B2 compared with the babbling equilibrium, which improves the payoff of l and h-types and thereby, eases their incentive constraints. The other is that, in the remaining case of B1, the continuation equilibrium is non-interior so that the spread of the agent's allocation to A across different types are smaller, which means that the variance of equilibrium allocation is reduced and this enhances the social welfare.

Proposition 6 warrants welfare improvement by mediation for l values roughly lower than $-0.81h$ (and larger than $-h$). This bound stems from the truth-telling IC of the less biased type. In the next section we modify the protocol to relax this constraint in order to identify a significantly broader range of parameter values for which mediation may improve welfare.

5.3 Modified Protocol

Below we modify the protocol with a view to relaxing the truth-telling IC of l-type. Since the IC of n-type is lax in Protocol P, we can relax IC of l-type by reducing n-type's payoff. We do this by introducing noise to the mediator's instruction when $(m_1, m_2) = (n, n)$. We show that the modified protocol increases expected welfare for much wider parameter range than Protocol P. However, the increase in the expected welfare is lower than under Protocol P due to noisy specialization. Therefore Protocol P dominates the modified protocol whenever it constitutes a mediated equilibrium.

Protocol Q: The same as Protocol P with just one change that when $(m_1, m_2) = (n, n)$ the mediator instructs S as before with prob $(1-q)$, but instructs B1 with prob $q \in (0, 1)$.

Then, the continuation equilibrium is the same as in Protocol P after S and after B2, but different after B1 as explained below.

Consider the continuation game after B1. Types l and h know that the opponent is n-type for sure as before. But, an n-type's posterior on the opponent's type is now h and l with probability $\frac{1}{2+q}$ each and n with probability $\frac{q}{2+q}$. That is, the agent's posterior belief on the other's type does not depend on the agent's identity, but it differs depending on their own type. This renders Lemma 2 inapplicable.

Hence, we derive a symmetric continuation equilibrium after B1 differently below. Let x, y and z be equilibrium allocation to area A of types l, n and h, respectively. The optimal responses of types l and h to y, respectively, are

$$x(y) = \begin{cases} 1+l-y & \text{if } y < 1+l \\ 0 & \text{if } y \geq 1+l \end{cases} \quad \text{and} \quad z(y) = \begin{cases} 1 & \text{if } y < h \\ 1+h-y & \text{if } y \geq h \end{cases}.$$

As $h < 1+l$ due to Assumption 1, the best response of n-type to $x(y)$ and $z(y)$ with probability $\frac{1}{2+q}$ each and y with probability $\frac{q}{2+q}$, is

$$Br(y) = \begin{cases} 1 - \frac{2+l-y+qy}{2+q} = \frac{-l+q+(1-q)y}{2+q} & \text{if } y < h \\ 1 - \frac{2+h+l-2y+qy}{2+q} = \frac{q-h-l+(2-q)y}{2+q} & \text{if } h \leq y < 1+l \\ 1 - \frac{1+h-y+qy}{2+q} = \frac{1+q-h+(1-q)y}{2+q} & \text{if } y \geq 1+l \end{cases}$$

Note that $Br(0) > 0$ while $Br(1) < 1$ and $Br(y)-y$ strictly decreases in all $y \in (0,1)$ with a value of $-(h+l)/(2+q) < 0$ when evaluated at $y = 1/2$. Thus, there is a unique fixed point of Br, denoted by $y^* < 1/2$.

Let q_h be such that $y^* = h$:

$$\frac{-l + q_h + (1-q_h)h}{2+q_h} = h \Leftrightarrow q_h = \frac{h+l}{1-2h} \in (0, 0.5).$$

Then,

$$\frac{-l+q+(1-q)y}{2+q} = y \Leftrightarrow y^* = \frac{q-l}{1+2q} < h \quad \text{if} \quad q < q_h, \quad \text{and}$$

$$\frac{q-h-l+(2-q)y}{2+q} = y \Leftrightarrow y^* = \frac{q-h-l}{2q} \in (h, 0.5) \quad \text{if} \quad q > q_h.$$

We now find q^* such that an n-type's expected payoffs from reporting n and l are identical. We proceed by presuming that $q^* \in (0, q_h)$, which we verify later. Given such q^*, if an n-type reports n and is instructed $B1$, then the total allocation to area A is $1+l$ and $1+y^*$ when the opponent is l and h-type, respectively, and $2y^*$ when n-type; if instructed S then it is 1. If she reports l and is instructed $B2$, then the allocation will be $(h-l)/2$ away from 1 when the opponent is of h or l type, while it will be 1 if instructed B1 which is the case when the opponent is n-type. Hence, q^* solves

$$\begin{aligned} \frac{1}{3}\Big(-l^2 - (\frac{q-l}{1+2q})^2 - q(1-2\frac{q-l}{1+2q})^2\Big) &= \frac{-(h-l)^2}{6} \\ \Longrightarrow \quad q^* &= \frac{-1+2h^2-2l-4hl-6l^2+(1+2l)\sqrt{1-2h^2+4hl+6l^2}}{2-4h^2+8hl+4l^2}. \end{aligned} \tag{12}$$

It is straightforward calculation to verify that this value of q^* is indeed in the interval $(0, q_h)$ as desired, which we defer to Appendix. Thus, we have found $q^* \in (0, q_h)$ in (12), such that an n-type's expected payoffs from reporting n and l are identical. Then, $y^* = \frac{q^*-l}{1+2q^*}$.

Provided that the agents report truthfully (to be verified later) and make allocation decisions as described above after receiving various instructions, the total expected welfare under Protocol Q is calculated as (1/9 of)

$$QW = -\Big(\frac{h-3l}{2}\Big)^2 - 2l^2 - 2\Big(\frac{h+l}{2}\Big)^2 - q^*\Big(1-2y^*\Big)^2 - 2y^{*2} - \Big(\frac{3h-l}{2}\Big)^2.$$

On the other hand, the total expected welfare of the babbling equilibrium is calculated from Table 1 as (1/9 of)

$$BW = -5h^2 + 2hl - 5l^2.$$

It is verified in Appendix (in the proof of Proposition 7) that QW exceeds BW so long as $|l| < h \leq 1/8$.

For the aforementioned behavior of the agent to constitute a PBE under the Protocol Q, however, the IC needs to be satisfied for the agents to report truthfully. It is trivially satisfied for n-type because q^* is derived above to satisfy it. (Note that reporting l and reporting h are the same thing in this Protocol.)

To verify IC for an l-type agent, observe that after reporting l truthfully, her subsequent allocation upon being instructed B2 is the unconstrained optimum to her opponent's allocation due to Lemma 2, and the same holds upon being instructed B1 as well because in that case her opponent's type is n for sure and thus, the total allocation is $x(y^*) + y^* = 1 + l$. Recall that an n-type agent's allocation is always the unconstrained optimum, which is 1 minus the expected allocation of her opponent which is between 0 and 1. Thus, the expected payoff after reporting l is the same as for an n-type agent and an l-type agent because the agent faces the same contingencies regardless of her type. After reporting n, on the other hand, an n-type agent's allocation is the unconstrained optimum upon being instructed B1, so an l-type agent's payoff cannot be higher in this case; upon being instructed S, however, an n-type agent still achieves her ideal allocation but an l-type agent doesn't if instructed to allocate 0 to A (because the her opponent allocate 1 to A). As an n-type agent is indifferent between reporting n and l, therefore, it follows the expected payoff of an l-type agent is higher after reporting l than after reporting n, establishing the IC for l-type.

For an h-type agent, after reporting h (or l) her subsequent allocation upon being instructed $B2$ is the unconstrained optimum due to Lemma 2 as before; upon being instructed B1, as in this case her opponent is of n-type and allocates $y^* < h$, she would allocate all her budget to area A so that the total allocation is $1 + y^*$. Thus, an h-type agent's expected payoff from reporting h falls short of that of an n-type by $(h - y^*)^2/3$. After reporting n, if instructed B1 an h-type agent would allocate $y^* + h \in (0, 1)$ to obtain the same expected payoff as an n-type agent (who would allocate y^*); if instructed S then she would achieve her ideal allocation when instructed to allocate 0 but h short when instructed 1 to area A. Thus, an h-type agent's expected payoff from reporting n falls short of that of an n-type by $(1-q^*)h^2/6$. We show in Appendix (in the proof of Proposition 7) that $(1-q^*)h^2/6$ exceeds $(h - y^*)^2/3$ so long as $h/3 < |l| < h \leq 1/8$, hence the IC for h-type is also satisfied. Therefore, Protocol Q expands considerably the set of parameter values (l, h) for which mediation improves the social welfare, as stated in the next result.

Proposition 7 *There is a PBE under Protocol Q such that the associated total expected welfare exceeds that under direct communication or no communication if*

$$h/3 < |l| < h \leq 1/8.$$

Proof. In Appendix. ■

6 Conclusions

We examine allocation of humanitarian aid by two potentially differently motivated agents to two equally needy areas A and B. Without communication the allocation of aid is inefficient resulting in gaps and duplication. Direct communication between the agents cannot improve the allocation because an agent biased to A would represent himself as biased to B with the aim of influencing the other agent to allocate more aid to area A. We show that a mediator who filters the information communicated by the agents and reveals it only partially to the agents can improve coordination of aid and social welfare.

It is often said that complexity and uncertainty of humanitarian emergencies causes coordination failure (see e.g. Tomasini and Wassenhove 2009). We show that the underlying incentive problem is present even in a setup which is not complex (there are two humanitarian organizations and two areas) and where there is no uncertainty about the humanitarian needs. Similarly, information overload has been reported to affect the unwillingness to share information. In our setup reporting and processing information is costless, yet direct communication is useless. Complexity, uncertainty and information overload are real concerns in humanitarian coordination. However, the remedy to coordination failure has to take into account the underlying incentive problem which is present even without these factors. Our remedy takes into account the sensitivities of information sharing: an information system that reveals only partially the information reported by the humanitarian organizations.

Our setup is in fact not specific to humanitarian aid but is applicable to any situation where several agents with potentially diverse motivations allocate funds to public goods. Such situations are common in the public sector. Our analysis also applies to a situation where the agents allocate time rather than funds.

In our model there is asymmetric information about the primary motivations. The analysis could be extended to asymmetric information about the budget size or uncertainty about the number of agents entering the emergency. An important next step for this research would be to introduce uncertainty about dynamically evolving needs, an issue that is endemic to sudden-onset humanitarian crises.

Appendix

Proof of Proposition 4. Recall that we first consider the case that $E(\alpha|\mu_1^{K_1}) \geq E(\alpha|\mu_2^{K_2})$ so that $E(\alpha|\mu_1^1) \leq E(\alpha|\mu_i^k) \leq E(\alpha|\mu_1^{K_1})$ for any $1 \leq k \leq K_i$ and $i \in \{1, 2\}$.

If $E(\alpha|\mu_1^1) = E(\alpha|\mu_1^{K_1})$ then $E(\alpha|\mu_i^k)$ is of the same value for all $1 \leq k \leq K_i$ and $i \in \{1, 2\}$, which must be $(h + l)/3$. Consequently, by Lemma 2 the total allocation for each type realisation is the same as that without communication as described in Table 1.

Consider the alternative case that $E(\alpha|\mu_1^1) < E(\alpha|\mu_1^{K_1})$ so that

$$E(\alpha|\mu_1^1) < (h + l)/3 < E(\alpha|\mu_1^{K_1}), \quad \text{thus} \quad \mu_1^{K_1}(h) > 0.$$

Note that the solution value of a_1^h is interior under the posterior (μ_1^1, μ_2^k) for any $k \in \{1, \cdots, K_2\}$ by Lemmas 2 and 3. On the other hand, the solution value of a_1^h is non-interior when $(\mu_1^{K_1}, \mu_2^1)$ by the next result.

Lemma 8 *If $E(\alpha|\mu_2) \leq (h + l)/3 < E(\alpha|\mu_1)$, then the continuation solution value of a_1^h is non-interior under (μ_1, μ_2).*

Proof. Suppose to the contrary that a_1^h is interior. Then, by Lemma 3, a_2^l must be non-interior, i.e, $a_2^n < |l|$. In such a continuation equilibrium, we would have

$$\begin{aligned} a_1^n &= 1 - E(a_2) = 1 - (1 - \mu_2^l)a_2^n - \mu_2^h h \quad \text{and} \\ a_2^n &= 1 - E(a_1) = 1 - a_1^n - \mu_1^h h - \mu_1^l l. \end{aligned}$$

Solving this simultaneous equations, we get

$$a_1^n = \frac{-h(\mu_2^h - \mu_1^h(1 - \mu_2^l)) + l\mu_1^l(1 - \mu_2^l) + \mu_2^l}{\mu_2^l}; \quad a_2^n = \frac{h(\mu_2^h - \mu_1^h) - l\mu_1^l}{\mu_2^l}$$

Note that a_1^n is increasing in μ_1^h. As $(h+l)/3 < E(\alpha|\mu_1) = \mu_1^h h + \mu_1^l l$ implies $\mu_1^h h > (h + l)/3 - \mu_1^l l$, it follows that a_1^n achieves minimum value of $\frac{3\mu_2^l + h(1-3\mu_2^h-\mu_2^l)+l(1-\mu_2^l)}{3\mu_2^l}$ at $\mu_1^h = ((h+l)/3-\mu_1^l l)/h$, which in turn decreases in μ_2^h. As $E(\alpha|\mu_2) = \mu_2^h h+\mu_2^l l \leq (h + l)/3$ implies $\mu_2^h h \leq (h + l)/3 - \mu_2^l l$, it follows that a_1^n achieves minimum value of $1 - (h - 2l)/3$ at $\mu_2^h = ((h + l)/3 - \mu_2^l l)/h$. This would imply that $a_1^n + h > 1 - (h - 2l)/3 + h = 1 + 2(h + l)/3 > 1$, i.e., a_1^h would be non-interior, contrary to our supposition, completing the proof. ■

Recall that the solution value of a_1^n is interior in all continuation games. Note that the optimization problem (3) is identical for all types when the control variable is redefined as $x = a-t_1$. Hence, different types of agent 1 in a given continuation game obtain the same utility level so long as they achieve the unconstrained optimum, i.e., when their solution values are interior. Thus, in particular, agent 1 of both n-type and h-type obtains the same continuation utility level after sending message

m_1^1 (thus the belief pair in the continuation game is $(\mu_1, \mu_2) = (\mu_1^1, \mu_2^k)$ for any $k \in \{1, \cdots, K_2\}$) because both types achieve unconstrained optimum as discussed above. After sending message $m_1^{K_1}$, on the other hand, agent 1 of n-type obtains a weakly larger continuation utility level as agent 1 of h-type, and sometimes a strictly larger level (in particular, when agent 2 sends m_2^1, so that $(\mu_1, \mu_2) = (\mu_1^{K_1}, \mu_2^1)$) by the next result.

Lemma 9 *Let a_i^* be the unconstrained optimal allocation of agent i of t-type relative to an allocation vector $a_j = (a_j^l, a_j^n, a_j^h) \in [0,1]^3$ of the other agent with posterior $\mu_j = (\mu_j^l, \mu_j^n, \mu_j^h)$. Then, her utility decreases by y^2 if her allocation is y away from a_i^*.*

Proof. From the FOC we have

$$a_i^* = 1 + t - \mu_j^l a_j^l - \mu_j^n a_j^n - \mu_j^h a_j^h = 1 + t - E(a_j|\mu_j).$$

Hence, when allocation changes by y from a_i^* the utility decreases by

$$-\mu_j^l(E(a_j|\mu_j) - a_j^l)^2 - \mu_j^n(E(a_j|\mu_j) - a_j^n)^2 - \mu^h(E(a_j|\mu_j) - a_j^h)^2$$

$$+\mu_j^l(E(a_j|\mu_j) - a_j^l - y)^2 + \mu_j^n(E(a_j|\mu_j) - a_j^n - y)^2 + \mu^h(E(a_j|\mu_j) - a_j^h - y)^2$$

$$= -2y\left[\mu_j^l(E(a_j|\mu_j) - a_j^l) + \mu_j^n(E(a_j|\mu_j) - a_j^n) + \mu^h(E(a_j|\mu_j) - a_j^h)\right] + y^2 \;=\; y^2. \quad \blacksquare$$

Therefore, as $\mu_1^{K_1}(h) > 0$ implies that agent 1 of h-type weakly prefers sending $\mu_1^{K_1}$ to μ_1^1, it follows that agent 1 of n-type should strictly prefer sending $\mu_1^{K_1}$ to μ_1^1. In addition, as agent 1 of l-type always obtains unconstrained optimum after sending $m_1^{K_1}$, she should also strictly prefer sending $\mu_1^{K_1}$ to μ_1^1 by a similar argument, implying $\mu_1^1(h) = 1$, a contradiction. This establishes that $E(\alpha|\mu_1^1) < E(\alpha|\mu_1^{K_1})$ is not possible in the case currently considered, namely when $E(\alpha|\mu_1^{K_1}) \geq E(\alpha|\mu_2^{K_2})$, and thus, $E(\alpha|\mu_1^1) = E(\alpha|\mu_1^{K_1})$ must hold and consequently, by Lemma 2, the equilibrium allocation is the same as that without communication as explained above.

It remains to consider the case that $E(\alpha|\mu_1^{K_1}) < E(\alpha|\mu_2^{K_2})$. Wlog, assume $E(\alpha|\mu_1^1) < E(\alpha|\mu_2^1)$, so that

$$E(\alpha|\mu_1^1) < E(\alpha|\mu_2^1) < (h+l)/3 < E(\alpha|\mu_1^{K_1}) < E(\alpha|\mu_2^{K_2}).$$

Then, five observations below, [1]–[5], follow.

[1] $\mu_1^{K_1}(h) > 0$ and $\mu_2^{K_2}(h) > 0$: Immediate from the inequalities above.

[2] $\mu_1^1(n) = 0$, and $\mu_1^1(l) > \frac{2h-l}{3(h-l)}$: The continuation solution value is always interior for either player of n-type. For agent 1 of h-type, the continuation solution value is always interior after sending m_1^1 by Lemma 3, but it is non-interior after sending $m_1^{K_1}$ with positive probability by Lemma 8. As agent 1 of h-type must weakly prefer sending $m_1^{K_1}$ to m_1^1, this implies that agent 1 of n-type must strictly

prefer sending $m_1^{K_1}$ to m_1^1 and thus, that $\mu_1^1(n) = 0$. Then, $\mu_1^1(l) > \frac{2h-l}{3(h-l)}$ follows from $E(\alpha|\mu_1^1) < (h+l)/3$.

[3] $E(\alpha|\mu_1^2) \geq E(\alpha|\mu_2^1)$: Suppose otherwise. Then, $\mu_1^2(n) = 0$ and $\mu_1^2(l) > \frac{2h-l}{3(h-l)}$ by the same reasoning as in [2] above applied to μ_1^2, and thus we may assume $E(\alpha|\mu_1^1) < E(\alpha|\mu_1^2) < E(\alpha|\mu_2^1)$ because messages m_1^1 and m_1^2 can be identified if $E(\alpha|\mu_1^1) = E(\alpha|\mu_1^2)$. Then, it follows from (5) that agent 1 of h-type would strictly prefer sending μ_1^1 to μ_1^2, contradicting $E(\alpha|\mu_1^1) < E(\alpha|\mu_1^2)$.

[4] There is $m_2^\kappa \in M_2$ such that $E(\alpha|\mu_2^\kappa) > E(\alpha|\mu_1^{K_1})$ and agent 1's net benefit of sending $m_1^{K_1}$ rather than m_1^1 conditional on $\mu_2 = \mu_2^\kappa$ is strictly lower for l-type than for n-type : Suppose otherwise. Then, agent 1's unconditional net benefit of sending $m_1^{K_1}$ rather than m_1^1 is no lower for l-type than for n-type, hence agent 1 of l-type must strictly prefer sending $m_1^{K_1}$ to m_1^1, contradicting [2].

[5] $\mu_2^\kappa(h) > 0$ and agent 2's net benefit of sending m_2^κ rather than m_2^1 conditional on $\mu_1 = \mu_1^1$ is weakly larger for h-type than for n-type : Suppose otherwise. Then, agent 2's unconditional net benefit of sending m_2^κ rather than m_2^1 is strictly larger for n-type than for h-type; since the net benefit is no lower for l-type than n-type, it would follow that agent 2 of both l-type and n-type must strictly prefer sending m_2^κ to m_2^1, contradicting $E(\alpha|\mu_2^1) < (h+l)/3$.

In light of Lemma 9, consider the continuation equilibrium allocation $a_1 = (a_1^l, a_1^n, a_1^h)$ and $a_2 = (a_2^l, a_2^n, a_2^h)$ under (μ_1^1, μ_2^κ). The proof proceeds in steps (a)–(d) below.

(a) $a_1^n < a_2^n$ and $a_2^h = 1$: by Lemma 3 and Lemma 8.

(b) $a_1^n < l$ and $a_1^l = 0$: Suppose that $a_1^n \geq l$ so that a_1^l is an interior solution and consequently,

$$a_2^n = 1 - a_1^n - E(\alpha|\mu_1^1). \tag{$b1$}$$

By Lemma 9 and (4) above, $\hat{a}_1^n < l$ must hold where $\hat{a}_i^n$ $(i = 1, 2)$ is the solution value after $(\mu_1^{K_1}, \mu_2^\kappa)$, which has the following two contradictory implications. First, $\hat{a}_1^n < l$ would imply that $E(\hat{a}_1|\mu_1^{K_1}) > \hat{a}_1^n + E(\alpha|\mu_1^{K_1})$ so that

$$\hat{a}_2^n = 1 - E(\hat{a}_1|\mu_1^{K_1}) < 1 - \hat{a}_1^n - E(\alpha|\mu_1^{K_1}). \tag{$b2$}$$

Second, $\hat{a}_1^n = 1 - E(\hat{a}_2|\mu_2^\kappa) < l \leq a_1^n = 1 - E(a_2|\mu_2^\kappa)$ implies $\hat{a}_2^n > a_2^n$, which in turn would imply $a_1^n - \hat{a}_1^n = E(\hat{a}_2|\mu_2^\kappa) - E(a_2|\mu_2^\kappa) < \hat{a}_2^n - a_2^n$ where the inequality follows from $\hat{a}_2^h = a_2^h = 1$, eventually leading to $\hat{a}_2^n > a_1^n + a_2^n - \hat{a}_1^n = 1 - \hat{a}_1^n - E(\alpha|\mu_1^1) > 1 - \hat{a}_1^n - E(\alpha|\mu_1^{K_1})$ where the equality follows from $(b1)$, contradicting $(b2)$.

(c) $E(a_1|\mu_1^1) - a_1^n > (h+l)/3$: Suppose otherwise. By Lemma 9 and (4) above, $\hat{a}_1^n < a_1^n$ must hold, for which we need $E(\hat{a}_1|\mu_1^{K_1}) < E(a_1|\mu_1^{K_1})$ which in turn implies that

$$E(a_1|\mu_1^{K_1}) - E(\hat{a}_1|\mu_1^{K_1}) < a_1^n - \hat{a}_1^n \tag{$b3$}$$

because $a_1^l = \hat{a}_1^l = 0$. Moreover, because $\hat{a}_1^n = 1 - E(\hat{a}_2|\mu_2^\kappa) < a_1^n = 1 - E(a_2|\mu_2^\kappa)$ implies $\hat{a}_2^n > a_2^n$ and thus $a_2^h = \hat{a}_2^h = 1$, it follows that $E(\hat{a}_2|\mu_2^\kappa) - E(a_2|\mu_2^\kappa) <$

$\hat{a}_2^n - a_2^n$. Together with $a_1^n = 1 - E(a_2|\mu_2^\kappa)$ and $\hat{a}_1^n = 1 - E(\hat{a}_2|\mu_2^\kappa)$, this implies that $a_1^n - \hat{a}_1^n = E(\hat{a}_2|\mu_2^\kappa) - E(a_2|\mu_2^\kappa) < \hat{a}_2^n - a_2^n = E(a_1|\mu_1^1) - E(\hat{a}_1|\mu_1^{K_1}) \leq E(a_1|\mu_1^{K_1}) - E(\hat{a}_1|\mu_1^{K_1})$, contradicting $(b3)$, where the last inequality follows from $E(a_1|\mu_1^{K_1}) \geq a_1^n + E(\alpha|\mu_1^{K_1}) > a_1^n + (h+l)/3$ and the supposition $E(a_1|\mu_1^1) - a_1^n \leq (h+l)/3$.

(d) $E(a_2|\mu_2^\kappa) - a_2^n \leq (h+l)/3$: Suppose otherwise. By Lemma 9 and (5) above, $a_2^n \leq \breve{a}_2^n$ must hold, where $\breve{a}_i^n (i = 1, 2)$ is the solution value after (μ_1^1, μ_2^1). This requires that $\breve{a}_1^n \leq a_1^n$ which implies that

$$0 \leq E(a_1|\mu_1^1) - E(\breve{a}_1|\mu_1^1) \leq a_1^n - \breve{a}_1^n. \qquad (b4)$$

As $E(a_2|\mu_2^\kappa) > a_2^n + (h+l)/3$ by supposition and $E(\breve{a}_2|\mu_2^1) < \breve{a}_2^n + (h+l)/3$ due to $E(\alpha|\mu_2^1) < (h+l)/3$, we have $E(\breve{a}_2|\mu_2^1) - E(a_2|\mu_2^\kappa) < \breve{a}_2^n - a_2^n = E(a_1|\mu_1^1) - E(\breve{a}_1|\mu_1^1) \leq a_1^n - \breve{a}_1^n$, where the equality follows from $a_2^n = 1 - E(a_1|\mu_1^1)$ and $\breve{a}_2^n = 1 - E(\breve{a}_1|\mu_1^1)$ and the last inequality from $(b4)$. However, from $a_1^n = 1 - E(a_2|\mu_2^\kappa)$ and $\breve{a}_1^n = 1 - E(\breve{a}_2|\mu_2^1)$ we in turn deduce that $a_1^n - \breve{a}_1^n = E(\breve{a}_2|\mu_2^1) - E(a_2|\mu_2^\kappa) < a_1^n - \breve{a}_1^n$, a contradiction.

However, from $a_1^n = 1 - E(a_2|\mu_2^\kappa)$ and $a_2^n = 1 - E(a_1|\mu_1^1)$ we get

$$E(a_2|\mu_2^\kappa) - a_2^n = 1 - a_1^n - a_2^n \quad \text{and} \quad E(a_1|\mu_1^1) - a_1^n = 1 - a_1^n - a_2^n,$$

verifying that (c) and (d) cannot hold at the same time. This proves that $E(\alpha|\mu_1^{K_1}) < E(\alpha|\mu_2^{K_2})$ is impossible. ■

Proof that $q^* \in (0, q_h)$. To show that $q^* > 0$, note first that because $-2l - 4hl - 6l^2$ is concace in l and $(1 + 2l)\sqrt{1 - 2h^2 + 4hl + 6l^2}$ is increasing in $l \in (-1/8, 0)$, the numerator of q^* in (12) is positive if its value is positive both at $l = -h$ and $l = 0$, which can be verified by routine calculations. As the denominator is also positive, q^* is verified to be positive.

To show that $q^* < q_h$, first note that $q^* = q_h = 0$ when $l = -h$. Note further that the denominator of q_h is smaller than that of q^* for $l \in (-h, 0)$: $2 - 4h^2 + 8hl + 4l^2 - 1 + 2h = 1 + 2h + 8hl - 4h^2 + 4l^2 > 1 + 2h - 4h^2 > 0$ where the first inequality follows because $8hl + 4l^2$ increases in l. Thus, the value of q^* increases when the denominator is replaced by $1 - 2h$, and consequently, it suffices to show that the derivative of the numerator of q_h wrt l exceeds that for q^* for $l \in (-h, 0)$. Since the former is 1, we show that the latter is no higher below.

The derivative of the numerator of q^* wrt l is calculated as

$$-2 - 4h - 12l + \frac{2(1 + h - 2h^2 + 3l + 6hl + 12l^2)}{\sqrt{1 - 2h^2 + 4hl + 6l^2}} \qquad (13)$$

The derivative of the fraction in (13) wrt h is

$$\frac{2(1 + 4h^3 + 4l - 12h^2 l + 12l^3 - 2h(1 - 4l - 6l^2))}{(1 - 2h^2 + 4hl + 6l^2)^{3/2}}$$

which is positive because i) the denominator is positive and ii) the numerator is increasing in $l \in (-h, 0)$ as its derivative wrt l is $8(1-3h^2+h(2+6l)+9l^2) > 0$, and iii) the value of numerator at $l = -h$ is $2(1-6h-8h^2+16h^3) > 0$ for $h \in (0, 1/8)$. Hence, (13) is bounded above by

$$-2+4l-12l+\left.\frac{2(1+h-2h^2+3l+6hl+12l^2)}{\sqrt{1-2h^2+4hl+6l^2}}\right|_{h=1/8}$$

$$= -2-8l+\frac{35+120l+384l^2}{2\sqrt{62+32l+384l^2}} \le -2-8l+\left.\frac{35+120l+384l^2}{2\sqrt{62+32l+384l^2}}\right|_{l=-1/8} = \frac{5}{8}.$$

Moreover, it is bounded below by

$$-2-4h-12l+\left.\frac{2(1+h-2h^2+3l+6hl+12l^2)}{\sqrt{1-2h^2+4hl+6l^2}}\right|_{h=-l}.$$

This proves that $q^* < q_h$ as desired. ■

Proof of Proposition 7. It remains to verify that (1) QW exceeds BW, and that (2) the IC is satisfied for h-type if $h/3 < |l| < h \le 1/8$.

(1) To show QW exceeds BW, treat $QW(q)$ as a function of $q \in (0,1)$ when $y = \frac{q-l}{1+2q}$, so that it suffices to show that $QW(q^*) > BW$. Then, it is easily calculated that $QW'(q) = \frac{-1+4l^2}{(1+2q)^2} < 0$, i.e, $QW(q)$ monotonically decreases as q increases from 0 to 1. Hence, we can find a unique $\hat{q}$ at which QW equals BW: $\hat{q} = \frac{2h^2-2l^2}{1-4h^2} \in (0,1)$. Consequently, it now suffices for us to show that $q^* < \hat{q}$. Let q^{**} denote q^* with $\sqrt{1-2h^2+4hl+6l^2}$ replaced by 1. Then, $q^{**} > q^*$ and moreover, $\hat{q} - q^{**} = \frac{(h+l)^2(1-4l^2)}{(1-4h^2)(1-2h^2+4hl+2l^2)} > 0$ because $1-2h^2+4hl+2l^2$ is increasing in l from a positive value of $1-4h^2$ at $l=-h$. This proves $\hat{q} > q^{**} > q^*$ as desired.

(2) Recall from the discussion preceding Proposition 7 that it remains to show that $(1-q^*)h^2/6 \ge (h-y^*)^2/3$, or equivalently, that $(1-q^*)h^2/2 \ge (h-y^*)^2$.

Note that y^* is concave in l because $\frac{\partial^2 y^*}{\partial l^2} = \frac{-3+8h^2}{(1-2h^2+4hl+6l^2)^{3/2}} < 0$. Hence, $(h-y^*)^2$ is convex in l. Since it is routinely verified that the derivative of $(h-y^*)^2$ wrt l is 0 when evaluated at $l=-h$, it further follows that $(h-y^*)^2$ increases in $l \in (-h, 0)$.

Moving on to q^*, as the denominator, $2-4h^2+8hl+4l^2$, is increasing in l, q^* is bounded above by when the denominator is evaluated at $l=-h$:

$$q^* < \frac{-1+2h^2-2l-4hl-6l^2+(1+2l)\sqrt{1-2h^2+4hl+6l^2}}{2-8h^2}.$$

In addition, as $1-2h^2+4hl+6l^2$ decreases in $l < -h/3$ and thus is bounded above by $1-2h^2+4hl+6l^2|_{l=-h} = 1$, we have

$$q^* < \bar{q} := \frac{2h^2-4hl-6l^2}{2-8h^2} \quad \text{if} \quad l < -\frac{h}{3}.$$

As $\bar{q}$ increases in $l < -h/3$, it follows that $(1-\bar{q})h^2/2$ decreases in $l < -h/3$. Furthermore, we have

$$\left.\frac{(1-\bar{q})h^2}{2} - (h-y^*)^2\right|_{l=-\frac{h}{3}} = \frac{h^2(3-16h^2)}{6-24h^2} - \left(h + \frac{9-6h-28h^2-3\sqrt{9-24h^2}}{12h+6\sqrt{9-24h^2}}\right)^2$$

$$= h^2\left[\frac{(3-16h^2)}{6-24h^2} - \left(1 + \frac{(9-3\sqrt{9-24h^2})/h-6-28h}{12h+6\sqrt{9-24h^2}}\right)^2\right]. \qquad (14)$$

Note the followings regarding (14).

i) It converges to 0 from above as $h \to 0$ because $\lim_{h\to 0}\frac{9-3\sqrt{9-24h^2}}{h} = \lim_{h\to 0}\sqrt{\frac{81}{h^2}} - \sqrt{\frac{81}{h^2} - 9\cdot 24} = 0$ where the latter equality stems from $\frac{d}{dx}\sqrt{x} \to 0$ as $x \to \infty$;

ii) The derivative of the first term in the brackets, $\frac{(3-16h^2)}{6-24h^2}$, is $-\frac{4h}{3(1-4h^2)^2} > -0.2$ for $0 < h < 1/8$;

iii) The derivative of the second term in the brackets, $\left(1+\frac{(9-3\sqrt{9-24h^2})/h-6-28h}{12h+6\sqrt{9-24h^2}}\right)^2$, is lower than -0.5 for $0 < h < 1/8$.

To verify iii), note that the derivative of the squared term (what is squared) is calculated as

$$\frac{\left[-9\sqrt{3}-32\sqrt{3}h^3+9\sqrt{3-8h^2}+h(12+20h)(\sqrt{3}-\sqrt{3-8h^2})\right]/h^2}{2\sqrt{3-8h^2}\left(2h+\sqrt{9-24h^2}\right)^2}. \qquad (15)$$

The derivative of the numerator and of the denominator of this are, resp.,

$$\frac{2(36h^2+80h^4-16h^3\sqrt{9-24h^2}-(9-6h)(3-\sqrt{9-24h^2}))}{h^3\sqrt{3-8h^2}}, \quad \text{and} \qquad (16)$$

$$\frac{24(2h+\sqrt{9-24h^2})(1-4h^2-2h\sqrt{9-24h^2})}{\sqrt{3-8h^2}}. \qquad (17)$$

The denominator of both is positive. The numerator of (16) is shown by routine calculation to be strictly concave with a slope of 0 at $h = 0$, so that (16) is strictly negative for $h \in (0, 1/8)$. The numerator of (17) is shown by routine calculation to monotonically decrease to a value greater than 0.6 at $h = 1/8$. Thus, numerator of (15) decreases in h while the denominator increases in h.

It is straightforward calculations to show that he denominator of (15) increases from a value approx. 31.1769 when $h = 0$ to approx. 34.4404 when $h = 1/8$, and that the numerator of (15) decreases to approx. -23.7036 when $h = 1/8$. In addition, the numerator of (15) approaches a limit value of $-36/\sqrt{3} \approx -20.7846$ as $h \to 0$, as shown below:

$$
\begin{aligned}
& \lim_{h\to 0} \frac{-9\sqrt{3} - 32\sqrt{3}h^3 + 9\sqrt{3-8h^2} + h(12+20h)(\sqrt{3}-\sqrt{3-8h^2})}{h^2} \\
= & \lim_{h\to 0} \frac{(12h-9)(\sqrt{3}-\sqrt{3-8h^2})}{h^2} \\
= & \lim_{h\to 0} \left(12 - \frac{9}{h}\right)\left(\sqrt{\frac{3}{h^2}} - \sqrt{\frac{3}{h^2}-8}\right) \\
= & \lim_{h\to 0} -\frac{9}{h}\left(\sqrt{\frac{3}{h^2}} - \sqrt{\frac{3}{h^2}-8}\right) \in \left(\frac{-9\cdot 8}{2h\sqrt{\frac{3}{h^2}-8}}, \frac{-9\cdot 8}{2h\sqrt{\frac{3}{h^2}}}\right) = \left(\frac{-36}{\sqrt{3-8h^2}}, \frac{-36}{\sqrt{3}}\right)
\end{aligned}
$$

where the inclusion to the interval follows because $\frac{d}{dx}\sqrt{x} = \frac{1}{2\sqrt{x}}$. Note that this interval approaches to a point $-36/\sqrt{3}$.

Consequently, (15) is no higher than $-20/35 < -0.5$. As (15) is the the derivative of "the squared term", it further follows that iii) above holds because derivative of $f(x)^2$ is $2f(x)f'(x)$ where in the current case $f(x)$ is "the squared term", so that $f'(x) < -0.5$ and $f(x) \in (0.5, 2/3)$.

Combining i)–iii), we deduce that (14) is positive. As $(h-y^*)^2$ increases in l while $(1-\bar{q})h^2/2$ decreases in l for the relevant range as shown above, it follows that $(1-\bar{q})h^2/2 > (h-y^*)^2$. Together with the fact that $q^* < \bar{q}$, this proves that $(1-q^*)h^2/2 > (h-y^*)^2$, as desired. ■

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