

# Monotone Equilibria in Signalling Games

Shuo Liu

Harry Pei\*

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## Abstract

We study the monotonicity of sender's equilibrium strategy with respect to her type in signalling games. We present counterexamples to show that when the sender's payoff is non-separable, the Spence-Mirrlees condition cannot rule out equilibria in which the sender uses non-monotone strategies. We also provide sufficient conditions under which all equilibria are monotone, which require that the sender's payoff having strictly increasing differences between the state and the action profile and being monotone with respect to each player's action. Our sufficient conditions fit into a number of applications, including advertising, warranty provision, education and job assignment.

**Keywords:** signalling game, monotone equilibrium, Spence-Mirrlees condition, monotone-supermodularity, quasi-concavity preserving, increasing absolute differences over distributions

**JEL Classification:** C72, D82

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\*Liu: Universität Zürich, shuo.liu@econ.uzh.ch. Pei: Massachusetts Institute of Technology, harrydp@mit.edu. We thank Daron Acemoglu, Kyle Bagwell, Ying Chen, Drew Fudenberg, Kevin He, Navin Kartik, Alexey Kushnir, SangMok Lee, Nick Netzer, Parag Pathak, John Quah, Armin Schmutzler, Juuso Toikka, Carl Veller, Muhamet Yildiz and seminar participants at Johns Hopkins University, MIT, the University of Zurich and the 2017 Lisbon Meetings in Game Theory and Applications for comments and feedback. Shuo Liu acknowledges the hospitality of Columbia University and the financial support by the Swiss National Science Foundation (Doc. Mobility grant P1ZH P1\_168260). Errors are ours.

# 1 Introduction

Starting from the seminal contribution of Spence (1973), signalling games have become powerful tools to study strategic interactions under asymmetric information. In a typical signalling model, an informed *sender*, who has private information about the payoff environment (or her *type*), takes an action that can influence the behavior of an uninformed *receiver*. This game theoretic model helps researchers to understand phenomena such as education, limit pricing, the peacock’s tail, etc.

In virtually all applications of signalling games, players’ payoffs satisfy a well-known Spence-Mirrlees condition: The sender’s actions and types are ranked, such that a higher type has a comparative advantage in taking higher actions compared to a lower type. For example, it is less costly for a talented worker to receive more education (Spence 1973), it is more profitable for an efficient firm to cut prices (Milgrom and Roberts 1982), etc. Under this condition, it may seem intuitive to predict that the sender’s action is non-decreasing in her type, or in other words, the game’s outcome is *monotone*. Indeed, researchers often focus on such *monotone equilibria* in many applications of signalling games, see for example, Spence (1973, 1977), Ross (1977), etc.

In this paper, we assess the robustness of this monotonicity prediction. We focus on signalling games that satisfy a generalized version of the Spence-Mirrlees condition: the set of types and actions are complete lattices and the sender’s payoff exhibits strictly increasing differences between the state and her own action. An equilibrium is monotone if a higher type sender never plays a strictly lower action than a lower type.

We examine the monotonicity of *all* (Bayes) Nash equilibria in these signalling games. Our motivation for this is twofold. First, as pointed out by Fudenberg, Kreps and Levine (1988) and Weinstein and Yildiz (2013), refinements in extensive form games are sensitive to the modeling details. Therefore, it is important to evaluate the robustness of the monotonicity prediction against equilibrium selection. Second, monotone equilibria have desirable properties, making them straightforward to interpret, tractable to analyze and easy to compute (Athey 2001). Therefore, a result establishing the monotonicity of all equilibria can facilitate the characterization of the set of equilibrium strategies and outcomes.<sup>1</sup>

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<sup>1</sup>To address the concern that there is a plethora of equilibria in signalling games, we apply the following “double standard”: For counterexamples, we adopt stronger solution concepts such as sequential equilibrium (Kreps and Wilson 1982), equilibria that can survive the refinements proposed in Kohlberg and Mertens (1986), Cho and Kreps (1987), Banks and Sobel (1987), etc. When presenting positive results, we adopt weaker solution concepts such as Nash equilibrium.

We start with a counterexample showing that the Spence-Mirrlees condition *cannot* guarantee the monotonicity of the sender's equilibrium strategy. These non-monotone equilibria exist even when both players' payoffs are strictly supermodular functions with respect to the sender's type, the sender's action and the receiver's action. Furthermore, they can survive standard refinements as both players have strict incentives and the sender plays every action with strictly positive probability.

Compared to Spence (1973), non-monotone equilibria arise due to the *non-separability* of the sender's payoff, that is, her return from the receiver's action depends on her type. This occurs in a number of applications, such as a worker's preference over jobs depends on her talent. Intuitively, when jobs and talents are horizontally differentiated (Roy 1951) and the worker chooses which job-specific human capital to acquire (her action), a high type sender has an incentive to play a low action if doing so can induce the receiver to play a high action. The receiver has an incentive to play his high action after observing the sender's low action as he believes that the sender's type is high, making his belief self-fulfilling.

We then proceed to provide sufficient conditions under which all Nash equilibria are monotone. At the heart of our analysis is a *monotone-supermodular* condition, which requires in addition to the Spence-Mirrlees condition, that (1) the sender's payoff is strictly decreasing in her own action and is strictly increasing in the receiver's action, (2) the sender's payoff has increasing differences between the state and the receiver's action.<sup>2</sup> This fits into a number of applications, including the education signalling game where an employer assigns workers job positions after observing their years of education, the warranty provision game where a firm chooses the length of warranty and the amount of refund before a consumer chooses the quantity to purchase, etc.

Our first result (Theorem 1) shows that every equilibrium is monotone when the sender's payoff is monotone-supermodular and the receiver's action choice is binary. This fits into the warranty provision game when the consumer has unit demand. Intuitively, thanks to the binary choice assumption, every pair of distributions over the receiver's action can be ranked according to first-order stochastic dominance (FOSD). Since playing a higher action is more costly for the sender, she only has an incentive to do so when it can induce a more favorable response from the receiver. This implies that the ranking over the sender's equilibrium actions must coincide with the ranking over the distributions of the receiver's action that they induce. Since a high type sender has a stronger

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<sup>2</sup>Despite the monotone-supermodularity condition is not necessary in general, we use counterexamples to address why every component of this condition is not superfluous in subsection 4.3.

preference towards higher action profiles, she will never play a strictly lower action than a low type in any Nash equilibrium.

However, in games where the receiver has three or more actions, non-monotone equilibria can arise despite the sender's payoff being monotone-supermodular. This is because not every pair of the receiver's mixed actions can be ranked according to FOSD. Consequently, one cannot draw inference about the ranking of the receiver's responses based on the ranking of the sender's equilibrium actions.

We introduce two sets of sufficient conditions to address this issue. First, we show in Theorem 2 that every equilibrium is monotone if the sender's payoff is monotone-supermodular, the ranking over the receiver's action set is complete and the receiver's payoff satisfies a *quasiconcavity-preserving property* (QPP). QPP requires the receiver's payoff to be strictly quasi-concave in his own action under every belief about the state. A sufficient condition for QPP is that the receiver's payoff being strictly concave in his own action, which fits into the warranty provision game when the consumer faces decreasing marginal returns to quantity.<sup>3</sup> QPP implies that the receiver has at most two pure best replies in every circumstance, which must be adjacent elements in his action set. As a result, every pair of his *mixed best replies* can be ranked according to FOSD.

Second, we identify a novel condition on the sender's payoff under which every pair of the receiver's mixed actions can be ranked endogenously. We call this property *increasing absolute differences over distributions* (IADD). Theorem 3 shows that if the sender's payoff is monotone-supermodular and satisfies IADD, then every Nash equilibrium is monotone. Unlike Theorem 2, Theorem 3 (as well as Theorem 1) makes no reference to the receiver's payoff function and incentives, so the conclusion extends to richer environments such as the sender signalling to a population of heterogeneous receivers, the receiver having private information about his payoff, etc. We also establish a representation result that characterizes IADD (Proposition 1), which facilitates the application of our Theorem 3 to economic modeling.

**Literature Review.** Starting from Spence (1973), the monotonicity of outcome has become a natural prediction in various applications of signalling games to labor economics, industrial organization, corporate finance and biology. Our paper points out that even in environments where the Spence-Mirrlees condition is satisfied, such a prediction is *not* without loss when the sender's return from

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<sup>3</sup>In Appendix B.1, we relate QPP to a strict version of the signed-ratio monotonicity condition in Quah and Strulovici (2012) and provide a full characterization.

the receiver's action depends on her type. This contrasts to the alternative channels suggested in the literature through which non-monotone equilibria can arise, as the latter often require various departures from the standard signalling model. For example, Feltovich, Harbaugh and To (2002), Araujo, Gottlieb and Moreira (2007) show that if the receiver observes an exogenous signal that is informative about the sender's type, then there exist *countersignalling equilibria* in which the high type plays a low action to distinguish herself from the medium type. As shown in several papers on warranty provision (e.g. Gal-Or 1989, Balachander, 2001), non-monotone equilibria can also arise when the sender's actions cannot be perfectly observed.

This paper also contributes to the literature on supermodular incomplete information games. Most of the papers in this literature focus on simultaneous move games and establish the existence of monotone pure strategy Nash equilibrium (e.g. Athey 2001, McAdams 2003, Van Zandt and Vives 2007, Reny 2011).<sup>4</sup> Several papers establish the monotonicity of all equilibria in simultaneous move supermodular games, for example, Morris and Shin (1998) and the vast literature on global games. In multi-dimensional environments, McAdams (2006) shows that every equilibrium is outcome-equivalent to a monotone equilibrium in multi-unit uniform price auctions with risk neutral bidders and independent values. In contrast, we analyze the monotonicity of equilibria in *sequential move* games where players' payoff functions are supermodular, with one-shot signalling games a natural starting point.<sup>5</sup>

To the best of our knowledge, the question when it is without loss to focus on monotone equilibria has not been systematically analyzed in signalling game contexts. We take a step to close this gap by providing sufficient conditions under which all equilibria are monotone. Our conditions highlight the economic forces behind equilibrium monotonicity and our counterexamples illustrate how monotonicity can fail once they are relaxed. Furthermore, these conditions are easy to verify given the functional forms of players' payoffs, which are useful for future applied works.

We close this section by commenting on two specific results in the literature that are related to

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<sup>4</sup>Mensch (2016) studies dynamic incomplete information games with strategic complementarities and establishes the existence of monotone perfect Bayesian equilibrium.

<sup>5</sup>Complementarities in dynamic games are explored by Echenique (2004a, 2004b), that explain how intertemporal incentives can weaken the implications of complementarity and supermodularity. Despite we have established the monotonicity of all Nash equilibria in a signalling game context, a signalling game with supermodular payoff functions is not necessarily supermodular in its normal form and, therefore, the other attractive properties of simultaneous move supermodular games, such as the existence of extremal equilibria, monotone comparative statics, the tâtonnement algorithm to compute the set of equilibria, etc. cannot be applied to our setting.

our sufficient conditions. The first one is obtained by Cho and Sobel (1990). While the main focus of their paper is to analyze the uniqueness and strategic stability of the universally divine equilibrium outcomes, they also establish a result stating that the sender's strategy must be monotone in every equilibrium (Lemma 4.1, p. 393 - 394). Different from ours, their result *assumes* that the receiver's best response is always a pure strategy. The second related result is obtained in a recent work by Kartik, Lee and Rappoport (2017). Similar to our Theorem 3, they also identify a class of utility functions under which the sender will use a monotone strategy in every equilibrium. We will show in section 5 that our results neither nest theirs nor are nested by theirs.

## 2 The Model

Consider the following two-player signalling game. Player 1 (or sender, she) privately observes the realization of a payoff relevant state  $\theta \in \Theta$  (call it her *type*) and then chooses an action  $a_1 \in A_1$ . Player 2 (or receiver, he) has a prior belief  $\pi \in \Delta(\Theta)$  about  $\theta$ . He chooses  $a_2 \in A_2$  after observing  $a_1$ . Player  $i$ 's payoff is  $u_i(\theta, a_1, a_2)$  with  $i \in \{1, 2\}$ . Both players are expected utility maximizers. Let  $u_1(\theta, a_1, \alpha_2) \equiv \int_{a_2} u_1(\theta, a_1, a_2) d\alpha_2$  for every  $\alpha_2 \in \Delta(A_2)$ .

Throughout the paper, we assume that  $\Theta, A_1$  and  $A_2$  are finite lattices and  $\pi$  has full support.<sup>6</sup> We will comment on cases in which  $\Theta, A_1$  and  $A_2$  are infinite after stating our main results. We use  $\succ$  and  $\succeq$  to denote strict and weak orders on lattice sets. For two lattices  $X$  and  $Y$ , a mapping  $f : X \times Y \rightarrow \mathbb{R}$  exhibits *increasing differences* if for every  $x, x' \in X$  and  $y, y' \in Y$  with  $x \succ x'$  and  $y \succ y'$ :

$$f(x, y) - f(x', y) \geq f(x, y') - f(x', y'), \quad (2.1)$$

and it exhibits *strictly increasing differences* if the above inequality is strict (Topkis 1998). We introduce a condition on the sender's payoff, which generalizes the Spence-Mirrlees condition to discrete lattices:

**Definition 1** (Generalized Spence-Mirrlees Condition).  $u_1$  satisfies the generalized Spence-Mirrlees condition if it exhibits strictly increasing differences in  $(\theta, a_1)$ .

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<sup>6</sup>A set  $X$  is a lattice if there exists a partial order  $\succeq$  such that for every  $x, x' \in X$ ,  $x \vee x', x \wedge x' \in X$ , where  $x \vee x'$  is the smallest element above both  $x$  and  $x'$ ,  $x \wedge x'$  is the largest element below both  $x$  and  $x'$ .

Intuitively, this generalized Spence-Mirrlees condition requires that a higher type sender has a comparative advantage in playing higher actions compared to a lower type.<sup>7</sup> This fits into most applications of signalling theory, including the education game in which receiving education is less costly for a more talented worker (Spence 1973), the beer-quiche game in which drinking beer is more pleasant for the strong sender (Cho and Kreps 1987), the warranty provision game in which providing lengthier warranty is less costly for a high quality firm (Gal-Or 1989), etc. Our condition is also satisfied in many multi-dimensional signalling models, such as Quinzii and Rochet (1985), Araujo et al. (2007), etc.

**Strategies & Equilibrium.** The sender's strategy is  $\sigma_1 : \Theta \rightarrow \Delta(A_1)$  and the receiver's strategy is  $\sigma_2 : A_1 \rightarrow \Delta(A_2)$ . Let  $\sigma_1^\theta \in \Delta(A_1)$  be the (possibly mixed) action played by type  $\theta$ , which gives  $\sigma_1 = (\sigma_1^\theta)_{\theta \in \Theta}$ .

The solution concept is Nash equilibrium (henceforth equilibrium), which consists of a strategy profile  $\sigma \equiv (\sigma_1, \sigma_2)$  such that  $\sigma_i$  best responds to  $\sigma_{-i}$  for every  $i \in \{1, 2\}$ . Since the game is finite, an equilibrium exists. Next, we introduce the definitions of *monotone strategy* and *monotone equilibrium*:

**Definition 2** (Monotone Strategy & Monotone Equilibrium).  $\sigma_1$  is a monotone strategy if for every  $\theta \succ \theta'$ , there exist no  $a_1 \in \text{supp}(\sigma_1^\theta)$  and  $a'_1 \in \text{supp}(\sigma_1^{\theta'})$  such that  $a_1 \prec a'_1$ . An equilibrium  $(\sigma_1, \sigma_2)$  is monotone if  $\sigma_1$  is a monotone strategy.

In words, a strategy is monotone if a low type sender never plays a strictly higher action than a high type. When the order on  $A_1$  is complete (or  $A_1$  is one-dimensional), the monotonicity of  $\sigma_1$  is equivalent to the following:

$$\min_{a_1} \{ \text{supp}(\sigma_1^\theta) \} \succeq \max_{a_1} \{ \text{supp}(\sigma_1^{\theta'}) \} \text{ for every } \theta \succ \theta'. \quad (2.2)$$

That is to say, if type  $\theta'$  plays  $a_1$  with positive probability, then every type higher than  $\theta'$  must be playing actions that are higher or equal to  $a_1$  with probability 1.

We are interested in examining the monotonicity of *all* Nash equilibria in signalling games, and in

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<sup>7</sup>For alternative versions of the Spence-Mirrlees condition, see Engers (1987), Cho and Sobel (1990), etc.

particular, games in which the sender's payoff satisfies the generalized Spence-Mirrlees condition.<sup>8</sup> The choice of a weak solution concept makes our positive results presented in section 4 (Theorems 1-3) robust against equilibrium selection. However, due to the plethora of equilibria in signalling games, one might argue that we should restrict attention to a subset of equilibria that can survive standard refinements instead of all Nash equilibria. To address this concern, we will adopt the more stringent solution concept of sequential equilibrium (Kreps and Wilson 1982) when presenting counterexamples. To make it even more convincing, we also require them to survive the refinements proposed in Kohlberg and Mertens (1986), Cho and Kreps (1987), Banks and Sobel (1987), etc.

**Remark on Monotonicity.** Our notion of monotonicity can be viewed as a strong one. For example, when  $A_1$  is one-dimensional, (2.2) implies that  $\text{supp}(\sigma_1^\theta)$  dominates  $\text{supp}(\sigma_1^{\theta'})$  in strong set order for every  $\theta \succ \theta'$ . Nevertheless, it is worth to note that all counterexamples in our paper (Examples 1 - 4) will violate the weaker notion of monotonicity based on strong set order, making them more convincing. In contrast, all positive results in this paper (Theorems 1 - 3) apply under our more demanding monotonicity requirement, which strengthens their implications.

When  $A_1$  is multi-dimensional, our definition of monotone strategies is no longer equivalent to but is only implied by condition (2.2). This is due to the incompleteness of the order on  $A_1$ . Thus, one may be interested in further strengthening the robust prediction about the sender's strategy by insisting that (2.2) holds even when  $A_1$  is multi-dimensional. In Appendix B.2, we use an example to illustrate the difficulty of obtaining positive results when Definition 2 is replaced by (2.2) in multi-dimensional environments.

### 3 Counterexample: Existence of Non-Monotone Equilibria

In this section, we present a counterexample which shows that the generalized Spence-Mirrlees condition cannot guarantee the monotonicity of the sender's equilibrium strategy even in  $2 \times 2 \times 2$  games.

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<sup>8</sup>The existence of monotone equilibria is often trivial given our weak solution concept. For example, when  $u_1$  is strictly decreasing in  $a_1$  (which is satisfied in many costly signalling games, such as Spence education signalling and the beer-quiche game), let  $\underline{a}_1$  be the smallest element in  $A_1$  and let  $\hat{a}_2 \in \arg \max_{a_2} \int_{\Theta} u_2(\theta, \underline{a}_1, a_2) d\pi(\theta)$ , then the strategy profile  $\sigma$  with  $\sigma_1(\theta) = \underline{a}_1 \forall \theta \in \Theta$  and  $\sigma_2(a_1) = \hat{a}_2 \forall a_1 \in A_1$  constitutes a Nash equilibrium. This is monotone according to Definition 2.

**Example 1.** Consider the following  $2 \times 2 \times 2$  game:

$\theta = \theta_1$	$h$	$l$
$H$	2, 2	0, 0
$L$	1, 1	0, 0

$\theta = \theta_0$	$h$	$l$
$H$	-1, -1/2	1, 0
$L$	0, -1	5/2, 1/4

The sender observes  $\theta$  and chooses between  $H$  and  $L$ . The receiver chooses between  $h$  and  $l$  after observing the sender's action choice. We leave the receiver's prior belief unspecified as it plays no role. One can check that according to the orders  $\theta_1 \succ \theta_0$ ,  $H \succ L$  and  $h \succ l$ , the generalized Spence-Mirrlees condition is satisfied. In fact, these payoffs even satisfy a stronger notion of complementarity, that is, both  $u_1$  and  $u_2$  are strictly supermodular functions of the triple  $(\theta, a_1, a_2)$ .<sup>9</sup> Intuitively, there are complementarities between players' actions as well as between the state and the action profile.

However, the above signalling game admits the following non-monotone equilibrium. The sender plays  $L$  if her type is  $\theta_1$  and plays  $H$  if her type is  $\theta_0$ . The receiver, who could perfectly learn the state from the sender's action, plays  $l$  after observing  $H$  and plays  $h$  after observing  $L$ . Clearly, the sender's strategy is non-monotone and no player has any incentive to deviate.<sup>10</sup>

In fact, since players have strict incentives and there are no off-path beliefs, the above strategy profile and its induced belief system also form a sequential equilibrium (Kreps and Wilson 1982). Moreover, it cannot be refined away using the selection criteria proposed in Kohlberg and Mertens (1986), Cho and Kreps (1987), Banks and Sobel (1987). Since players' incentives are strict, this equilibrium is also robust against perturbations on the game's payoff matrices.

We argue that this non-monotone equilibrium is driven by three features of the game: sequential moves, non-separable payoff (of the sender) and interdependent values. When players move sequentially, every  $a_1$  induces a distribution over  $a_2$ . As a result, the sender is effectively choosing a distribution over *action profiles* instead of just her own action. Because  $u_1$  is *non-separable* with

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<sup>9</sup>Let  $X$  be a lattice. A function  $f : X \rightarrow \mathbb{R}$  is *strictly supermodular* if  $f(x \vee x') + f(x \wedge x') \geq f(x) + f(x')$  for every  $x, x' \in X$ , and the inequality is strict if  $\{x, x'\} \neq \{x \vee x', x \wedge x'\}$ .

<sup>10</sup>In the context of this game, the non-monotone equilibrium is Pareto dominated by a monotone equilibrium. However, this is not a general feature and the Pareto dominance criteria cannot always refine away all non-monotone equilibria. In Example 3 (section 4.3) when the prior probability of state  $\theta_0$  is sufficiently high, our non-monotone equilibrium Pareto dominates the alternative unique monotone equilibrium, in which both types play  $H$  and player 2 plays  $l$  regardless of what the sender does.

respect to  $\theta$  and  $a_2$ , her preferences over the receiver's actions also vary with the state. Therefore, her state contingent action choice depends not only on her comparative advantage in  $a_1$  but also on her preferences over  $a_2$ . Since the receiver's best response to  $a_1$  depends on his belief about the state (i.e. values are *interdependent*), choosing  $h$  after observing  $L$  and choosing  $l$  after observing  $H$  can be rationalized despite there are complementarities between players' actions in  $u_1$  and  $u_2$ . In our non-monotone equilibrium, the receiver believes that the state is  $\theta_1$  after observing  $L$  and the state is  $\theta_0$  after observing  $H$ , which provides the sender an incentive to use non-monotone strategies and makes the receiver's belief self-fulfilling.

While sequential moves and interdependent values are standard in signalling games, non-separability of the sender's payoff distinguishes our model from the classic education signalling game (Spence 1973) and the beer-quiche game (Cho and Kreps 1987). In these examples, the sender's valuations of money and fighting do not depend on her type. Nevertheless, non-separable payoffs arise naturally in many other economic applications. For example, consider a firm (receiver) offering a worker (sender) a job after observing her education. The worker's preferences over jobs depend on her type (for example, her taste and talent) no matter whether the jobs are horizontally differentiated (Roy 1951) or vertically differentiated (Waldman 1984, Gibbons and Waldman 1999).<sup>11</sup> Non-separability also occurs in many applications in industrial organization, some of which will be discussed in section 5.

It is also worth to point out that the existence of non-monotone equilibrium in Example 1 does not contradict the well-known results in Van Zandt and Vives (2007) on *simultaneous move* Bayesian supermodular games. This is because once we maintain the pre-specified orders over players' actions, a signalling game with supermodular payoffs (Example 1) is not supermodular in its normal form.<sup>12</sup>

## 4 Sufficient Conditions for Monotone Equilibrium

In this section, we introduce sufficient conditions that guarantee the monotonicity of all equilibria. At the heart of our analysis is the following *monotone-supermodular* condition on the sender's payoff:

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<sup>11</sup>When jobs are horizontally differentiated, different types of workers prefer different kinds of jobs, as in Roy (1951)'s hunting-fishing example. When jobs are vertically differentiated, the worker's gain from a job position depends on her talent due to the piece-rate incentive schemes, the prospects of promotion, etc.

<sup>12</sup>Echenique (2004a) shows that every game that has at least two pure Nash equilibria is supermodular if the analyst can flexibly choose the order over players' strategies. However, the results that are established under an arbitrary order cannot imply the monotonicity of the sender's action with respect to her type.

**Definition 3** (Monotone-Supermodular Condition). *The sender's payoff is monotone-supermodular if (i)  $u_1$  is strictly decreasing in  $a_1$  and strictly increasing in  $a_2$ , and (ii)  $u_1$  exhibits strictly increasing differences in  $(\theta, a_1)$  and increasing differences in  $(\theta, a_2)$ .*

Compared to the more demanding requirement that both  $u_1$  and  $u_2$  are strictly supermodular functions of  $(\theta, a_1, a_2)$ , our monotone-supermodular condition does not require any complementarities within players' actions, nor does it impose any restrictions on the receiver's payoff function. Nevertheless, it incurs two important requirements in addition to the generalized Spence-Mirrlees condition. First, the sender's payoff exhibits increasing differences between the state and the receiver's action. This includes the separable payoff (i.e., there exist  $f : A_1 \times A_2 \rightarrow \mathbb{R}$  and  $c : \Theta \times A_1 \rightarrow \mathbb{R}$  such that  $u_1(\theta, a_1, a_2) = f(a_1, a_2) + c(\theta, a_1)$ ) as a special case. It also fits into many other applications where payoffs are non-separable by nature. For example, in warranty provision games, the firm's per unit profit (sales price minus the expected refund paid to the consumers) increases with its product quality, and therefore, its total profit exhibits increasing differences between its quality and the quantity sold. In education signalling games in which a firm assigns workers to various job positions after observing their years of education, more talented workers receive higher benefits from higher level jobs due to the piece-rate incentive schemes and better prospects of promotion.

Second, the sender's payoff is monotone with respect to her own action and the receiver's action in appropriate directions.<sup>13</sup> This is natural in many applications. For example, it is costly for the firm to provide lengthier warranties and higher refunds, but it can benefit when consumers increase their purchasing quantities. Similarly, workers face higher opportunity costs to receive more education but they can benefit from more decent job positions.

In the next two subsections (4.1 and 4.2), we state results that establish the monotonicity of all equilibria in signalling games where the sender's payoff is monotone-supermodular. The role of the monotone-supermodular condition in our results will be discussed in subsection 4.3. We will elaborate in section 5 how the assumptions of our results fit into the classic applications of signalling games in industrial organization and labor economics, and outline their implications in these settings.

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<sup>13</sup>Our results also hold when the sender's payoff is increasing in her own action and decreasing in the receiver's action. However, non-monotone equilibria can exist when the sender's payoff is strictly increasing (or strictly decreasing) in both players' actions (see Example 3 in subsection 4.3).

## 4.1 Binary Action Games

In this subsection, we study games in which the receiver's action choice is binary, i.e.  $|A_2| = 2$ . This holds the warranty provision game when the consumer has unit demand, i.e.  $a_2 \in \{0, 1\}$ . Our first result below states that for these games, monotone-supermodularity alone is sufficient to guarantee the monotonicity of all equilibria.

**Theorem 1.** *If  $|A_2| = 2$  and the sender's payoff is monotone-supermodular, then every equilibrium is monotone.*

PROOF. Let  $A_2 \equiv \{\bar{a}_2, \underline{a}_2\}$  with  $\bar{a}_2 \succ \underline{a}_2$ . Suppose towards a contradiction that in some equilibrium  $\sigma$ , there exist  $\theta \succ \theta'$  and  $a_1 \succ a'_1$  such that  $\sigma_1^\theta(a'_1) > 0$  and  $\sigma_1^{\theta'}(a_1) > 0$ . Let  $\alpha_2 \equiv \sigma_2(a_1)$  and  $\alpha'_2 \equiv \sigma_2(a'_1)$  be the mixed actions played by the receiver after observing  $a_1$  and  $a'_1$ , respectively. Since type  $\theta$  prefers  $(a'_1, \alpha'_2)$  to  $(a_1, \alpha_2)$  and type  $\theta'$  prefers  $(a_1, \alpha_2)$  to  $(a'_1, \alpha'_2)$ , we have:

$$u_1(\theta, a'_1, \alpha'_2) \geq u_1(\theta, a_1, \alpha_2) \quad (4.1)$$

and

$$u_1(\theta', a_1, \alpha_2) \geq u_1(\theta', a'_1, \alpha'_2). \quad (4.2)$$

These together imply that:

$$u_1(\theta, a'_1, \alpha'_2) - u_1(\theta, a_1, \alpha_2) \geq 0 \geq u_1(\theta', a'_1, \alpha'_2) - u_1(\theta', a_1, \alpha_2). \quad (4.3)$$

Because  $u_1$  is strictly decreasing in  $a_1$ , (4.2) also implies that  $u_1(\theta', a'_1, \alpha_2) > u_1(\theta', a_1, \alpha_2) \geq u_1(\theta', a'_1, \alpha'_2)$ . This further implies that  $\alpha_2$  must attach a higher probability to  $\bar{a}_2$  compared to  $\alpha'_2$ , as the sender's payoff is strictly increasing in  $a_2$ . Therefore, we have  $\theta \succ \theta'$ ,  $a_1 \succ a'_1$  and  $\alpha_2$  dominates  $\alpha'_2$  in the sense of first-order stochastic dominance (FOSD). Since  $u_1$  has strictly increasing differences in  $(\theta, a_1)$  and increasing differences in  $(\theta, a_2)$ , we have:

$$u_1(\theta, a'_1, \alpha'_2) - u_1(\theta, a_1, \alpha_2) < u_1(\theta', a'_1, \alpha'_2) - u_1(\theta', a_1, \alpha_2), \quad (4.4)$$

which contradicts (4.3). □

The intuition of Theorem 1 is as follows. When  $|A_2| = 2$ , every pair of distributions over the receiver's action can be ranked according to FOSD. Since playing a higher action is more costly for the sender, she only has an incentive to do so when it induces a more favorable response from the receiver. This implies that the ranking over the sender's equilibrium actions must coincide with the ranking over the receiver's (possibly mixed) actions that they induce. Because a high type sender has a stronger preference towards higher action profiles, she will never play a strictly lower action than a low type.

Since the above proof makes no reference to the receiver's incentives, our monotonicity property also applies to every ex ante rationalizable strategy (Bernheim 1984; Pearce 1984). In fact, only monotone strategies can survive the first round of elimination. The irrelevance of the receiver's incentives also makes it clear that our result immediately extends to cases where the receiver has private information about his preferences, the sender is signalling to a population of receivers with heterogeneous preferences, etc.

Theorem 1 can also be generalized to signalling games with infinite  $A_1$  and  $\Theta$  with two caveats.<sup>14</sup> First, when the type space is infinite, Nash equilibrium needs to be defined at the interim stage after the sender observes her type. This is to ensure that the sender will play a best reply at every state. Second, when  $A_1$  is infinite, some of the actions in the support of a sender's strategy can be suboptimal. Hence, the monotonicity condition in Definition 2 is too demanding. Nevertheless, we show in Appendix B.3 that the sender's equilibrium strategy is *almost surely monotone* in the following sense: For every  $\theta \succ \theta'$  and  $a_1 \in \text{supp}(\sigma_1^\theta)$ , the probability that type  $\theta'$  plays an action strictly higher than  $a_1$  equals zero.

Theorem 1 also has the following implication on *repeated* signalling games where the state is perfectly persistent, the sender's stage game payoff is monotone-supermodular and the receiver's action choice is binary. For every pair of states  $\theta \succ \theta'$  and every Nash equilibrium  $(\sigma_1, \sigma_2)$  of the repeated signalling game, if playing the highest action in every period is the sender's best reply against  $\sigma_2$  in state  $\theta'$ , then according to  $\sigma_1$ , she will play the highest action with probability 1 at every on-path history in state  $\theta$ .<sup>15</sup> As shown in Pei (2017), this is an intermediate step towards establishing the commitment payoff theorem and the uniqueness of the sender's on-path equilibrium behavior in

<sup>14</sup>The existence of equilibrium is guaranteed by the monotonicity condition (see footnote 7).

<sup>15</sup>However, the monotonicity of equilibria in the stage game does not imply the monotonicity of the sender's behavior strategy at every on-path history in the repeated signalling game. Therefore, our result cannot guarantee that the receiver will always positively update his belief about the sender's type after observing the sender playing her highest action.

reputation games.

## 4.2 Games with $|A_2| \geq 3$

In this subsection, we generalize our findings in binary action games to ones in which the receiver has more than two actions. To illustrate the difficulties, we first present a counterexample showing that the sender's payoff being monotone-supermodular is no longer sufficient to guarantee the monotonicity of all equilibria.

**Example 2.** Consider the following  $2 \times 2 \times 3$  game:

$\theta = \theta_1$	$h$	$m$	$l$
$H$	$2 - \varepsilon, 1$	$1 - 2\varepsilon, 0$	$-3\varepsilon, -2$
$L$	$2, 0$	$1, 1$	$0, 0$

$\theta = \theta_0$	$h$	$m$	$l$
$H$	$2 - 3\varepsilon, 0$	$1 - 3\varepsilon, 0$	$4\varepsilon, 0$
$L$	$2 - \varepsilon, 0$	$1, 2$	$8\varepsilon, 3$

Suppose  $\varepsilon \in (0, 1/8)$  and apply the rankings  $\theta_1 \succ \theta_0$ ,  $H \succ L$  and  $h \succ m \succ l$ . One can verify that the sender's payoff is monotone-supermodular. However, consider the following strategy profile: The sender plays  $L$  if  $\theta = \theta_1$ , and plays  $H$  if  $\theta = \theta_0$ . The receiver plays  $m$  after observing  $L$ , and plays  $h$  and  $l$  with equal probabilities after observing  $H$ . One can check that the sender's strategy is non-monotone although this strategy profile and its induced belief constitute a sequential equilibrium.<sup>16</sup>

Example 2 highlights the following issue: When  $|A_2| \geq 3$ , the *distributions* over the receiver's actions cannot be completely ranked via FOSD. In particular,  $u_1$  being monotone-supermodular does *not* imply the following:

- For every  $\alpha_2, \alpha'_2 \in \Delta(A_2)$ , if  $\alpha_2$  is preferred to  $\alpha'_2$  for some  $\theta \in \Theta$  when she plays  $a_1 \in A_1$ , then the sender's expected payoff difference between  $\alpha_2$  and  $\alpha'_2$  is increasing in her type conditional on  $a_1$ .

We proceed along two directions to address this challenge, leading to two monotonicity results. First, we introduce a property on the receiver's payoff under which every pair of his (pure or mixed) *best replies* can be ranked via FOSD. This, together with the monotone-supermodular condition on

<sup>16</sup>This counterexample is not driven by the receiver's non-generic payoff. Even when the receiver has strict preferences over  $A_2$  conditional on  $(\theta, a_1) = (\theta_0, H)$ , there still exists a non-monotone partial pooling equilibrium in which type  $\theta_1$  mixes between  $H$  and  $L$ , and type  $\theta_0$  always plays  $H$ .

the sender's payoff, implies the monotonicity of all equilibria (Theorem 2). Second, we identify a class of utility functions  $u_1$  which can endogenously generate a complete order on  $\Delta(A_2)$ . When the sender's payoff function belongs to this class and is monotone-supermodular, every equilibrium is monotone irrespective of the receiver's payoff (Theorem 3).

#### 4.2.1 Quasiconcavity-Preserving Property

For this part, we assume that  $A_2 \equiv \{a_2^1, \dots, a_2^n\}$  is completely ordered with  $a_2^1 \prec a_2^2 \prec \dots \prec a_2^n$ .<sup>17</sup> For every  $(\theta, a_1) \in \Theta \times A_1$  and  $i \in I \equiv \{1, 2, \dots, n-1\}$ , let

$$\gamma_\theta^{a_1}(i) \equiv u_2(\theta, a_1, a_2^i) - u_2(\theta, a_1, a_2^{i+1}) \quad (4.5)$$

be the receiver's payoff gain by decreasing his action locally, and let

$$\Gamma_{\tilde{\pi}}^{a_1}(i) \equiv \int \gamma_\theta^{a_1}(i) d\tilde{\pi} \quad (4.6)$$

be his expected payoff gain under belief  $\tilde{\pi} \in \Delta(\Theta)$ . We now recall the definition of *strict single-crossing* functions in Milgrom and Shannon (1994):

**Definition 4.** *Function  $\gamma: I \rightarrow \mathbb{R}$  satisfies the strict single-crossing property (SSCP) if for every  $i \in I$ ,  $\gamma(i) \geq 0$  implies that  $\gamma(j) > 0$  for every  $j \in I$  with  $j > i$ .*

If  $\gamma_\theta^{a_1}(\cdot)$  satisfies SSCP for every  $(\theta, a_1) \in \Theta \times A_1$ , then  $u_2(\theta, a_1, \cdot)$  is strictly quasi-concave in  $a_2$ . In that case, the receiver has at most two pure best replies to every  $(\theta, a_1)$ , which must be adjacent elements in  $A_2$ . This further implies that every pair of his (pure or mixed) best replies to a degenerate distribution on  $\Theta \times A_1$  can be ranked according to FOSD. However, some of the sender's actions may induce non-degenerate beliefs in some equilibria, so the issue of aggregating the single-crossing property arises. This motivates us to introduce a *quasiconcavity-preserving property* (QPP) on the receiver's payoff.

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<sup>17</sup>Our monotonicity result in this subsection (Theorem 2) can also be extended to settings where  $A_2$  is a multi-dimensional convex set.

**Definition 5** (Quasiconcavity-Preserving Property). *The receiver's payoff satisfies QPP if  $\Gamma_{\tilde{\pi}}^{a_1} : I \rightarrow \mathbb{R}$  satisfies SSCP for every  $(\tilde{\pi}, a_1) \in \Delta(\Theta) \times A_1$ .*<sup>18</sup>

A sufficient condition for QPP is  $\gamma_{\theta}^{a_1}(\cdot)$  being strictly increasing for every  $(\theta, a_1) \in \Theta \times A_1$ . This fits into the warranty provision game when the consumer faces decreasing marginal returns with respect to quantity. Intuitively,  $u_2$  is *strictly concave* in  $a_2$  when  $\gamma_{\theta}^{a_1}(\cdot)$  is strictly increasing. The latter implies QPP as strict concavity is preserved under positive linear aggregation. Nevertheless, strict concavity is by no means necessary for QPP. In Appendix B.1, we provide a full characterization of QPP by relating it to a strict version of the signed-ratio monotonicity condition introduced in Quah and Strulovici (2012).

Under QPP, the receiver's (pure or mixed) best replies to every  $(\tilde{\pi}, a_1) \in \Delta(\Theta) \times A_1$  can be ranked according to FOSD. This leads to our second result:

**Theorem 2.** *If (i) the order on  $A_2$  is complete, (ii) the sender's payoff is monotone-supermodular, and (iii) the receiver's payoff satisfies QPP, then every equilibrium is monotone.*

The proof follows along the same line as that of Theorem 1, which we omit to avoid repetition. Note that despite the extra condition on the receiver's payoff function, Theorem 2 only requires him to play a best reply against some  $\tilde{\pi} \in \Delta(\Theta)$  after every  $a_1 \in A_1$  on the equilibrium path. Therefore, the above monotonicity result does not depend on the receiver's belief updating process and applies to all outcomes under weaker solution concepts such as  $S^{\infty}W$  (Dekel and Fudenberg 1990) and iterative conditional dominance (Shimoji and Watson 1998), which are variants of rationalizability that can rule out the receiver's suboptimal plays at off-path information sets.<sup>19</sup> Moreover, when applying the elimination procedure for  $S^{\infty}W$ , all non-monotone strategies will be deleted after one round of elimination of weakly dominated strategy followed by another of round elimination of strictly dominated strategy. When applying iterative conditional dominance, all surviving strategies are monotone after two rounds of elimination.

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<sup>18</sup>A more general version of the QPP property when  $A_2$  is any subset of  $\mathbb{R}$  is introduced and characterized by Choi and Smith (2017). In the case where  $A_2$  is finite, our condition is equivalent to a strict version of theirs.

<sup>19</sup> $S^{\infty}W$  is the solution concept when applying one round elimination of weakly dominated strategies followed by iterative elimination of strictly dominated strategies. Dekel and Fudenberg (1990) show that it characterizes the set of rationalizable strategies when players entertain small amount of uncertainty about their opponents' payoffs. Shimoji and Watson (1998) show that iterative conditional dominance generalizes rationalizability in normal form games to extensive form games.

## 4.2.2 Increasing Absolute Differences over Distributions

In what follows, we take an alternative approach by introducing a condition on the sender's payoff that can guarantee the monotonicity of equilibria irrespective of the receiver's payoff. Unlike the previous subsection, we allow the order on  $A_2$  to be incomplete. As illustrated in Example 2, the main obstacle against equilibrium monotonicity is the lack of a complete order on  $\Delta(A_2)$ . We introduce the following *increasing absolute differences over distributions* condition (IADD) on the sender's payoff under which a complete order on  $\Delta(A_2)$  can be constructed endogenously.

**Definition 6** (Increasing Absolute Differences over Distributions). *The sender's payoff satisfies IADD if for every  $a_1 \in A_1$  and every  $\alpha_2, \alpha'_2 \in \Delta(A_2)$ , we have  $u_1(\theta, a_1, \alpha_2) - u_1(\theta, a_1, \alpha'_2)$  being either increasing in  $\theta$  and non-negative for all  $\theta \in \Theta$ , or decreasing in  $\theta$  and non-positive for all  $\theta \in \Theta$ .*

To make sense of the terminology, note that IADD implies that the absolute value of the difference  $u_1(\theta, a_1, \alpha_2) - u_1(\theta, a_2, \alpha'_2)$  is increasing in  $\theta$ .<sup>20</sup> Intuitively, if  $u_1$  satisfies IADD, then for every  $a_1 \in A_1$ , there exists a complete ordinal preference on  $\Delta(A_2)$  (denoted by  $\succsim_{a_1}$ ) that is shared among all types of senders. In addition, this ordinal ranking coincides with the one based on the intensity of preferences. In other words, if  $\alpha_2 \succsim_{a_1} \alpha'_2$ , then the difference in the sender's payoffs between  $(a_1, \alpha_2)$  and  $(a_1, \alpha'_2)$  must be increasing in  $\theta$ . This leads to our last monotonicity result:

**Theorem 3.** *If  $u_1$  is monotone-supermodular and satisfies IADD, then every equilibrium is monotone.*

PROOF. Suppose towards a contradiction that in some equilibrium  $(\sigma_1, \sigma_2)$ , there exist  $\theta \succ \theta'$  and  $a_1 \succ a'_1$  such that  $\sigma_1^\theta(a'_1) > 0$  and  $\sigma_1^{\theta'}(a_1) > 0$ . Let  $\alpha_2 \equiv \sigma_2(a_1)$ ,  $\alpha'_2 \equiv \sigma_2(a'_1)$  with  $\alpha_2, \alpha'_2 \in \Delta(A_2)$ . Since type  $\theta$  prefers  $(a'_1, \alpha'_2)$  to  $(a_1, \alpha_2)$ , and type  $\theta'$  prefers  $(a_1, \alpha_2)$  to  $(a'_1, \alpha'_2)$ , we have:

$$u_1(\theta, a'_1, \alpha'_2) \geq u_1(\theta, a_1, \alpha_2) \tag{4.7}$$

and

$$u_1(\theta', a_1, \alpha_2) \geq u_1(\theta', a'_1, \alpha'_2). \tag{4.8}$$

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<sup>20</sup>IADD is also necessary for  $|u_1(\theta, a_1, \alpha_2) - u_1(\theta, a_2, \alpha'_2)|$  to be increasing in  $\theta$  when  $\Theta$  is a continuum and  $u_1$  is a continuous function of  $\theta$ .

Since  $u_1$  is strictly decreasing in  $a_1$ , we have  $u_1(\theta', a'_1, \alpha_2) > u_1(\theta', a_1, \alpha_2)$ . Inequality (4.8) then implies that  $u_1(\theta', a'_1, \alpha_2) > u_1(\theta', a'_1, \alpha'_2)$ . Applying (4.7) and (4.8) we have:

$$u_1(\theta, a'_1, \alpha'_2) - u_1(\theta, a_1, \alpha_2) \geq u_1(\theta', a'_1, \alpha'_2) - u_1(\theta', a_1, \alpha_2). \quad (4.9)$$

Meanwhile, note that

$$u_1(\cdot, a'_1, \alpha'_2) - u_1(\cdot, a_1, \alpha_2) = u_1(\cdot, a'_1, \alpha'_2) - u_1(\cdot, a'_1, \alpha_2) + u_1(\cdot, a'_1, \alpha_2) - u_1(\cdot, a_1, \alpha_2).$$

Since  $u_1$  exhibits strictly increasing differences between  $\theta$  and  $a_1$ , we have:

$$u_1(\theta, a'_1, \alpha_2) - u_1(\theta, a_1, \alpha_2) < u_1(\theta', a'_1, \alpha_2) - u_1(\theta', a_1, \alpha_2). \quad (4.10)$$

In addition, IADD and  $u_1(\theta', a'_1, \alpha_2) - u_1(\theta', a'_1, \alpha'_2) > 0$  imply that:

$$u_1(\theta, a'_1, \alpha'_2) - u_1(\theta, a'_1, \alpha_2) \leq u_1(\theta', a'_1, \alpha'_2) - u_1(\theta', a'_1, \alpha_2). \quad (4.11)$$

Summing up (4.10) and (4.11), we obtain a contradiction against (4.9). Therefore, every equilibrium must be monotone.  $\square$

As a remark, since the order on  $\Delta(A_2)$  can be constructed endogenously under IADD, our result does not rely on the pre-specified order on  $A_2$ , nor does it rely on the monotone-supermodularity condition on  $u_1$  with respect to  $a_2$ . In fact, it is clear from the above proof that once  $u_1$  satisfies IADD, all equilibria are monotone if  $u_1$  is strictly decreasing in  $a_1$  and exhibits strictly increasing differences in  $(\theta, a_1)$ .

Furthermore, since the proof of Theorem 3 makes no reference to the receiver's rationality and incentives, it possesses the same robustness properties as Theorem 1. That is, all ex ante rationalizable strategies of the sender must also be monotone. This monotonicity result continues to hold when the receiver has private information about his payoff, when the sender is signalling to a population of receivers with heterogeneous preferences, etc. In addition, Theorem 3 immediately extends to cases where  $A_2$  is infinite as the cardinality of  $A_2$  plays no role in the above proof. Finally, extensions of Theorem 3 to cases where  $\Theta$  and  $A_1$  are infinite are subject to the same cautions mentioned in

subsection 4.1 and Appendix B.3, with the main issue being that the support of the sender's strategy may include suboptimal actions that are played with zero probability.

In order to apply Theorem 3, it is necessary to verify whether IADD is satisfied. To facilitate this process, we fully characterize the functional form restrictions of IADD in the following proposition:

**Proposition 1.**  $u_1$  satisfies IADD if and only if there exist functions  $f : A_1 \times A_2 \rightarrow \mathbb{R}$ ,  $v : \Theta \times A_1 \rightarrow \mathbb{R}_+$  and  $c : \Theta \times A_1 \rightarrow \mathbb{R}$  with  $v(\theta, a_1)$  increasing in  $\theta$ , such that:

$$u_1(\theta, a_1, a_2) = f(a_1, a_2)v(\theta, a_1) + c(\theta, a_1). \quad (4.12)$$

PROOF. See Appendix A. □

**Remark on IADD.** IADD enables us to construct endogenous orders on  $\Delta(A_2)$ . Nevertheless, as shown in Kartik et al. (2017) and Kushnir and Liu (2017), there are other conditions on players' payoff functions under which we could obtain a complete order over distributions. These include the *single-crossing expectational differences* (SCED) and the *monotone expectational differences* (MED) in Kartik et al. (2017), and the *increasing differences over distributions* (IDD) in Kushnir and Liu (2017).

When applied to the same probability space, IADD is more demanding than MED and SCED. This is because, for example, IADD on  $\Delta(A_2)$  requires that (i)  $u_1(\theta, a_1, \alpha_2) - u_1(\theta, a_2, \alpha'_2)$  does not change sign when we vary  $\theta$  and (ii) its absolute value is increasing in  $\theta$ . These together imply that the expected difference  $u_1(\theta, a_1, \alpha_2) - u_1(\theta, a_2, \alpha'_2)$  is monotone in  $\theta$ .<sup>21</sup>

However, as shown in subsection 4.3, neither MED, SCED nor IDD on  $\Delta(A_2)$  is sufficient for our purpose. It is also important to note that IADD on  $\Delta(A_2)$  neither implies nor is implied by MED or SCED on  $\Delta(A_1 \times A_2)$ . We will further elaborate on this in the context of education signalling (section 5.2), which helps clarify the novel implications of Theorem 3 compared to a related result in Kartik et al. (2017).

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<sup>21</sup>In our signalling game context, IDD on  $\Delta(A_2)$  would require that for every  $a_1 \in A_1$  and every  $\alpha_2, \alpha'_2 \in \Delta(A_2)$ , the expected payoff differences  $u_1(\theta, a_1, \alpha_2) - u_1(\theta, a_1, \alpha'_2)$  is either strictly increasing, strictly decreasing, or constant in  $\theta$ . In contrast, IADD only implies that these differences are either increasing or decreasing. Thus, in general Kushnir and Liu (2017)'s IDD is only implied by the strict version of our IADD (i.e. for every  $a_1 \in A_1$  and  $\alpha_2, \alpha'_2 \in \Delta(A_2)$ ,  $|u_2(\theta, a_1, \alpha_2) - u_2(\theta, a_1, \alpha'_2)|$  is either constant or strictly increasing in  $\theta$ ).

### 4.3 Discussion

In this subsection, we argue that the monotone-supermodular condition on the sender's payoff plays an indispensable role in our analysis. In particular, we will show that neither the monotonicity nor the supermodularity part of the condition can be replaced by other appealing alternatives.

#### 4.3.1 Alternative Monotonicity Conditions

One may conjecture that the existence of non-monotone equilibria (e.g. the one in Example 1) is driven by the state dependence of the sender's *ordinal* preferences over  $a_2$ , or whether we could modify the monotonicity assumption on the sender's payoff by letting it to be strictly increasing (or strictly decreasing) in both  $a_1$  and  $a_2$ . However, the following counterexample suggests that these conjectures are not true.

**Example 3.** Consider the following  $2 \times 2 \times 2$  game:

$\theta = \theta_1$	$h$	$l$
$H$	2,2	0,0
$L$	1,1	-1/2,0

$\theta = \theta_0$	$h$	$l$
$H$	1/4, -1/2	1/8, 0
$L$	0, -1	-1/16, 1/4

One can verify that according to the order  $\theta_1 \succ \theta_0$ ,  $H \succ L$  and  $h \succ l$ , the sender's payoff satisfies the generalized Spence-Mirrlees condition. Moreover, as in Example 1, both  $u_1$  and  $u_2$  are supermodular functions of the triple  $(\theta, a_1, a_2)$ . Different from Example 1, the sender's ordinal preferences over  $a_1$  and  $a_2$  are state independent. In particular, the sender's payoff is strictly increasing in both  $a_1$  and  $a_2$ . However, her cardinal preferences over the receiver's actions still depend on the state. As a result, there exists a non-monotone equilibrium in which type  $\theta_1$  plays  $L$ , type  $\theta_0$  plays  $H$ , and the receiver plays  $h$  after observing  $L$  and plays  $l$  after observing  $H$ . One can also construct similar counterexamples in which the sender's payoff exhibits strictly increasing differences in  $(\theta, a_1)$ , increasing differences in  $(\theta, a_2)$  but is strictly decreasing in both  $a_1$  and  $a_2$ .

### 4.3.2 Single-Crossing Differences vs. Increasing Differences

In this part, we show that our strictly increasing difference condition on  $u_1$  cannot be replaced with the *strict single-crossing difference property* in Milgrom and Shannon (1994), which is well-known in the monotone comparative statics literature.

**Definition 7.** *The sender's payoff has strict single-crossing differences (SSCD) if for every  $\theta \succ \theta'$  and every  $(a_1, a_2) \succ (a'_1, a'_2)$ ,  $u_1(\theta', a_1, a_2) - u_1(\theta', a'_1, a'_2) \geq 0$  implies that  $u_1(\theta, a_1, a_2) - u_1(\theta, a'_1, a'_2) > 0$ .*

By definition, SSCD is a weaker property than strictly increasing differences. The following example shows that SSCD is not sufficient for guaranteeing the monotonicity of equilibria in signalling games, even when the sender's payoff satisfies our monotonicity condition.

**Example 4.** Consider the following  $2 \times 2 \times 2$  game:

$\theta = \theta_1$	$h$	$l$
$H$	1, 2	-3, 0
$L$	3, 1	-1, 0

$\theta = \theta_0$	$h$	$l$
$H$	1, 0	-2, 0
$L$	2, -1	-1, 0

Consider the orders  $\theta_1 \succ \theta_0$ ,  $H \succ L$  and  $h \succ l$ . One can check that, first,  $u_1$  is strictly increasing in  $a_2$  and is strictly decreasing in  $a_1$ . Second,  $u_1$  has SSCD although it fails to have increasing differences. Let  $\alpha_2 \equiv \frac{2}{3}h + \frac{1}{3}l$  and  $\alpha'_2 \equiv \frac{1}{3}h + \frac{2}{3}l$  be two mixed actions of the receiver, we have:

$$u_1(\theta_0, h, \alpha_2) - u_1(\theta_0, l, \alpha'_2) = 0 > -\frac{2}{3} = u_1(\theta_1, h, \alpha_2) - u_1(\theta_1, l, \alpha'_2). \quad (4.13)$$

When the receiver's prior belief attaches probability  $1/3$  to state  $\theta_1$ , one can proceed to construct the following non-monotone equilibrium: Type  $\theta_1$  plays  $L$  for sure, type  $\theta_0$  plays  $H$  and  $L$  each with probability  $1/2$ , the receiver plays  $\alpha_2$  after observing  $H$  and  $\alpha'_2$  after observing  $L$ .

In the above example, the receiver's best reply to the sender's action is mixed. SSCD only requires that  $u_1(\theta, a_1, a_2) - u_1(\theta, a'_1, a'_2)$  has the strict single-crossing property for every pair of *pure* action profiles that can be ranked. This does not imply that  $u_1(\theta, a_1, \alpha_2) - u_1(\theta, a'_1, \alpha'_2)$  is also strict

single-crossing for every  $(a_1, \alpha_2), (a'_1, \alpha'_2) \in A_1 \times \Delta(A_2)$  with  $a_1 \succ a'_1$  and  $\alpha_2$  FOSDs  $\alpha'_2$ .<sup>22</sup> This leaves open the possibility of (4.13), which leads to the existence of non-monotone equilibria.

## 5 Applications

In this section, we revisit two classic applications of signalling games in industrial organization and labor economics. We apply our sufficient conditions to establish the monotonicity of all equilibria in these games and discuss the relationships between our results and the existing ones in the literature.

### 5.1 Advertising and Warranty Provision

Consider a firm (sender) selling products to a consumer (receiver). Let  $\theta \in \Theta \subset \mathbb{R}$  be the product's quality, which is the firm's private information. For simplicity, we assume that the per unit sales price is exogenous, which is normalized to 1. Every product sold has a positive probability of breakdown, which depends on its quality. The firm chooses a 3-dimensional action:  $a_1 \equiv (a_1^{ad}, a_1^{len}, a_1^{re}) \in A_1 \subset \mathbb{R}_+ \times \mathbb{R}_+ \times [0, 1]$ , where  $a_1^{ad}$  is the intensity of advertising,  $a_1^{len}$  is the length of warranty, and  $a_1^{re}$  is the (per unit) refund the firm commits to pay if the product breaks down during the length of the warranty. The consumer chooses how many units to purchase after observing  $a_1$ , which is denoted by  $a_2 \in A_2 \subset \mathbb{N}$ .

Our monotone-supermodular condition requires that (i)  $u_1$  is strictly decreasing in the triple  $(a_1^{ad}, a_1^{len}, a_1^{re})$  and is strictly increasing in  $a_2$ , and (ii)  $u_1$  has strictly increasing differences in  $(\theta, a_1^{ad})$ ,  $(\theta, a_1^{len})$  and  $(\theta, a_1^{re})$ , and increasing differences in  $(\theta, a_2)$ . The first part of the monotonicity requirement is most straightforward, as advertising, providing lengthier warranty and more refund are all costly for the firm. Monotonicity also requires that, keeping other factors fixed, the firm's profit is higher when the consumer purchases larger quantities.<sup>23</sup>

Next, we justify the supermodular part. First, there are complementarities between  $\theta$  and  $a_1^{ad}$  when the cost of promoting a good product is lower than the cost of promoting a bad one. This can be driven by regulation policies, reputation concerns, umbrella branding (Wernerfelt 1988), etc. Second,

<sup>22</sup>In fact, since  $|A_1| = |A_2| = 2$  in this example, the payoff function  $u_1$  also has SCED on both  $\Delta(A_1)$  and  $\Delta(A_2)$  (Kartik et al. 2017). However, it does not have SCED on the larger space  $\Delta(A_1 \times A_2)$ .

<sup>23</sup>This rules out cases in which the low quality seller will lose money when offering the equilibrium warranty/refund policy of the high quality seller. Nevertheless, it still fits into a number of cases of economic interest.

there are complementarities between  $\theta$  and  $a_1^{re}$  when higher quality product has lower probability of breakdown, so therefore, committing to a higher per unit refund is less costly. Similarly, the firm's per unit profit (defined as sales price minus expected refund payment) is strictly increasing in the product's quality, and therefore,  $u_1$  has strictly increasing differences in  $(\theta, a_2)$ . Finally, there are complementarities between  $\theta$  and  $a_1^{len}$  when breakdown arrives according to a time homogeneous Poisson process with intensity strictly decreasing in the product's quality (Gal-Or 1989).

As the firm's payoff is monotone-supermodular, it will use a monotone strategy in every equilibrium when the consumer has unit demand (Theorem 1), when the consumer faces decreasing marginal returns to quantities (Theorem 2), or when its payoff takes the following functional form (Theorem 3):

$$u_1(\theta, a_1, a_2) = \left( 1 - \underbrace{g(\theta, a_1^{len})}_{\substack{\text{prob. of breakdown} \\ \text{within } a_1^{len} \text{ periods}}} \cdot \overbrace{a_1^{re}}^{\text{per unit refund}} + f(\theta) \right) a_2 - \underbrace{c(\theta, a_1^{ad})}_{\text{cost of advertising}}, \quad (5.1)$$

where

- (i)  $g : \Theta \times \mathbb{R}_+ \rightarrow [0, 1]$  is strictly decreasing in  $\theta$ , strictly increasing in  $a_1^{len}$  and exhibits strictly decreasing differences in  $(\theta, a_1^{len})$ ,
- (ii)  $f : \Theta \rightarrow \mathbb{R}_+$  is strictly increasing, which captures the firm's benefit from initial sales beyond the sales price in a reduced form,<sup>24</sup> and
- (iii)  $c : \Theta \times \mathbb{R}_+ \rightarrow \mathbb{R}$  is strictly increasing in  $a_1^{ad}$  and exhibits strictly decreasing differences in  $(\theta, a_1^{ad})$ .

## 5.2 Education Signalling with Vertically Differentiate Jobs

Consider the following variant of the Spence (1973) education signalling model. Let  $\theta \in \Theta$  be the talent of the worker,  $a_1 \in A_1$  be the education the worker receives, and  $a_2 \in A_2$  be the job offered by the employer after he observes  $a_1$ .

The sender's payoff being monotone-supermodular implies that (i)  $u_1$  is strictly decreasing in  $a_1$  and strictly increasing in  $a_2$ , (ii)  $u_1$  exhibits strictly increasing differences between  $\theta$  and  $(a_1, a_2)$ .

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<sup>24</sup>This is relevant when the product is a newly introduced experience good (Nelson 1974; Milgrom and Roberts 1986). Nevertheless, the absence of  $f(\theta)$  will not affect the applicability of our monotonicity result.

The monotonicity assumption requires that receiving education is costly, and the jobs are *vertically* differentiated so that every worker prefers a higher level job.<sup>25</sup> For the supermodularity assumption, first,  $u_1$  exhibits strictly increasing differences in  $(\theta, a_1)$  when receiving education is less costly for more talented workers (Spence 1973). Second,  $u_1$  exhibits strictly increasing differences in  $(\theta, a_2)$  when the returns from a higher level job (relative to a lower level one) increases with the worker's talent, which is a well-established fact in the personnel economics literature.<sup>26</sup>

When the worker's payoff is monotone-supermodular, more talented workers receive more education in every equilibrium when there are only two jobs (Theorem 1). If the employer's payoff function is strictly concave in  $a_2$ ,<sup>27</sup> then Theorem 2 guarantees the monotonicity of all equilibria even when there are three or more jobs. Alternatively, suppose the worker's payoff function takes the following form:

$$u_1(\theta, a_1, a_2) = \underbrace{f(\theta, a_1)g(a_2)}_{\text{worker's return from job assignment}} - \underbrace{c(\theta, a_1)}_{\text{cost of education}}, \quad (5.2)$$

where  $f : \Theta \times A_1 \rightarrow \mathbb{R}_+$  is strictly increasing in  $\theta$ , and  $g : A_2 \rightarrow \mathbb{R}$  and  $c : \Theta \times A_1 \rightarrow \mathbb{R}$  are functions compatible with  $u_1$  being strictly decreasing in  $a_1$  and exhibiting strictly increasing differences in  $(\theta, a_1)$ . Intuitively, this means that the net (material) return from education is always negative, but it is strictly increasing with respect to the sender's type. Compared to the separable payoff function studied in Spence (1973), (5.2) allows the worker's return from a job offer to depend non-trivially on her type and education. Despite the non-separability of the sender's payoff function, Theorem 3 implies that every equilibrium is monotone regardless of how the employer evaluates various matches between jobs, talent and education.

Kartik et al. (2017) study a similar application, with  $a_2 \in \mathbb{R}_+$  being the wage offered by the firm. They show that if the worker's payoff function has SCED over  $\Delta(A_1 \times A_2)$ , then every equilibrium of this game is monotone. According to their characterization result,  $u_1$  has SCED over  $\Delta(A_1 \times A_2)$

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<sup>25</sup>If jobs are instead horizontally differentiated (Roy 1951), then the resulting payoff structure resembles Example 1, in which we have shown that non-monotone equilibria can exist.

<sup>26</sup>See for example, Waldman (1984) and Gibbons and Waldman (1999). Different types of workers receive different returns to a higher level job can be due to, for example, that the talent of a worker affects her prospects of promotion, the expected compensation she receives under piece-rate incentive schemes, etc.

<sup>27</sup>Concavity of  $u_2$  is satisfied if for every  $(\theta, a_1) \in \Theta \times A_1$ , there exists an ideal job assignment  $a_2^*(\theta, a_1)$  that maximizes  $u_2(\theta, a_1, \cdot)$ , and the employer incurs a quadratic loss when there is a mismatch between talent and jobs.

if and only if it takes the following functional form:

$$u_1(\theta, a_1, a_2) = g_1(a_1, a_2)f_1(\theta) + g_2(a_1, a_2)f_2(\theta) + h(\theta), \quad (5.3)$$

where both  $f_1$  and  $f_2$  are single-crossing functions that satisfy a ratio-ordered condition.<sup>28</sup> Their results provide insights on cheap talk games and education signalling games when the receiver's payoffs are unknown to the sender. However, their results are not applicable to education signalling games where the worker's payoff is given by (5.2) and  $c(\theta, a_1)$  cannot be written as the product of two functions  $c_1(\theta)$  and  $c_2(a_1)$ .<sup>29</sup> Our Theorem 3 accommodates these cases and implies the monotonicity of all equilibria.

## 6 Conclusion

This paper makes two main contributions. First, we show that equilibrium monotonicity does not follow from the Spence-Mirrlees condition nor is it implied by the complementarities in players' payoff functions. Our counterexamples are robust against equilibrium refinements and highlight the problems that can arise when the sender's returns from the receiver's action depend on her type. Second, we provide sufficient conditions under which all Nash equilibria are monotone. These conditions are easy to verify and fit into a number of applications, including advertising, warranty provision, education and job assignment, etc. In these scenarios, our results imply that it is without loss of generality to focus on monotone equilibria.

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<sup>28</sup>According to Kartik et al. (2017), for two single-crossing functions  $f_1, f_2 : \Theta \rightarrow \mathbb{R}$ ,  $f_1$  ratio dominates  $f_2$  if (i)  $\forall \theta \succeq \theta', f_1(\theta')f_2(\theta) \leq f_1(\theta)f_2(\theta')$ , and (ii)  $\forall \theta \succeq \hat{\theta} \succeq \theta', f_1(\theta')f_2(\theta) = f_1(\theta)f_2(\theta')$  if and only if  $f_1(\theta')f_2(\hat{\theta}) = f_1(\hat{\theta})f_2(\theta')$  and  $f_1(\hat{\theta})f_2(\theta) = f_1(\theta)f_2(\hat{\theta})$ . Functions  $f_1$  and  $f_2$  are ratio-ordered if either  $f_1$  ratio dominates  $f_2$  or  $f_2$  ratio dominates  $f_1$ .

<sup>29</sup>The cost function is not multiplicative separable in applications when  $c(\theta, a_1) = k(\theta)a_1 + t(a_1)$ , with  $t(a_1)$  being a fixed cost, interpreted as the cost of tuition, and  $k(\theta)a_1$  being a variable cost which depends on the worker's talent.

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## Appendix A

In this appendix, we establish Proposition 1 by proving a series of equivalence statements.

**Lemma A1.**  $u_1$  has IADD if and only if for every  $a_1 \in A_1$  and every  $\alpha_2, \alpha'_2 \in \Delta(A_2)$ , we have

$$u_1(\tilde{\theta}, a_1, \alpha_2) > u_1(\tilde{\theta}, a_1, \alpha'_2) \text{ for some } \tilde{\theta} \in \Theta \implies u_1(\theta, a_1, \alpha_2) - u_1(\theta, a_1, \alpha'_2) \text{ is increasing in } \theta. \quad (\text{A.1})$$

PROOF. The only-if part of the lemma is straightforward. Let us focus on the if part. To show that (A.1) implies IADD, it suffices to show that if  $u_1(\tilde{\theta}, a_1, \alpha_2) > u_1(\tilde{\theta}, a_1, \alpha'_2)$  for some  $\tilde{\theta}$ , then  $u_1(\theta, a_1, \alpha_2) \geq u_1(\theta, a_1, \alpha'_2)$  for all  $\theta \in \Theta$ .

Suppose towards a contradiction that there exist  $a_1 \in A_1, \alpha_2, \alpha'_2 \in \Delta(A_2)$ , and  $\tilde{\theta}, \hat{\theta} \in \Theta$ , such that  $u_1(\tilde{\theta}, a_1, \alpha_2) > u_1(\tilde{\theta}, a_1, \alpha'_2)$  and  $u_1(\hat{\theta}, a_1, \alpha_2) < u_1(\hat{\theta}, a_1, \alpha'_2)$ . Then, condition (A.1) implies that we have both  $u_1(\theta, a_1, \alpha_2) - u_1(\theta, a_1, \alpha'_2)$  and  $u_1(\theta, a_1, \alpha'_2) - u_1(\theta, a_1, \alpha_2)$  being increasing in  $\theta$ . Hence,  $u_1(\theta, a_1, \alpha_2) - u_1(\theta, a_1, \alpha'_2)$  must be constant for every  $\theta$ , which leads to a contradiction.  $\square$

Next, notice that an immediate implication of  $u_1$  satisfying IADD is that for every  $a_1 \in A_1$  and  $\alpha_2, \alpha'_2 \in \Delta(A_2)$ , the expected payoff difference  $u_1(\theta, a_1, \alpha_2) - u_1(\theta, a_1, \alpha'_2)$  is monotone in  $\theta$ . The following lemma fully characterizes this necessary condition of IADD.

**Lemma A2.**  $u_1(\theta, a_1, \alpha_2) - u_1(\theta, a_1, \alpha'_2)$  is monotone in  $\theta$  for every  $(a_1, \alpha_2, \alpha'_2) \in A_1 \times \Delta(A_2) \times \Delta(A_2)$  if and only if the sender's payoff has the following representation:

$$u_1(\theta, a_1, a_2) = f(a_1, a_2)v(\theta, a_1) + c(\theta, a_1) + g(a_1, a_2), \quad (\text{A.2})$$

where  $v : \Theta \times A_1 \rightarrow \mathbb{R}$  is an increasing function of  $\theta$ .

The proof of Lemma A2 is omitted as it immediately follows from the characterization results in Kartik et al. (2017) and Kushnir and Liu (2017). Therefore, it is without loss of generality to assume  $u_1$  taking the functional form in (A.2), which we will do for the rest of the proof.

We now proceed to characterize condition (A.1). To do this, let us first introduce some useful

notation. Let  $A_2 \equiv \{a_2^1, \dots, a_2^n\}$  with  $n \geq 2$ . For every  $a_1 \in A_1$ , let

$$\underline{v}^{a_1} \equiv \min_{\theta \in \Theta} v(\theta, a_1) \in \mathbb{R},$$

and

$$f^{a_1} \equiv (f(a_1, a_2^1), \dots, f(a_1, a_2^n)), g^{a_1} \equiv (g(a_1, a_2^1), \dots, g(a_1, a_2^n)) \in \mathbb{R}^n.$$

Finally, let  $\Gamma \equiv \{\gamma \in \mathbb{R}^n | \mathbf{1} \cdot \gamma = 0\}$ , where  $\mathbf{1} \equiv (1, 1, \dots, 1) \in \mathbb{R}^n$  and ‘ $\cdot$ ’ denotes the inner product of two vectors. We establish the following result.

**Lemma A3.** *Suppose that  $u_1$  has representation (A.2). Then,  $u_1$  satisfies (A.1) if and only if*

$$\forall (a_1, \gamma) \in A_1 \times \Gamma, (\underline{v}^{a_1} f^{a_1} + g^{a_1}) \cdot \gamma > 0 \implies f^{a_1} \cdot \gamma \geq 0. \quad (\text{A.3})$$

**PROOF.** (*If statement*) First, note that given the representation (A.2), condition (A.1) is equivalent to the requirement that for every  $(a_1, \gamma) \in A_1 \times \Gamma$  and every  $v \geq \underline{v}^{a_1}$ ,  $(v f^{a_1} + g^{a_1}) \cdot \gamma > 0 \implies f^{a_1} \cdot \gamma \geq 0$ . Suppose towards a contradiction that this does not hold for some  $(a_1, \gamma) \in A_1 \times \Gamma$  and some  $v \geq \underline{v}^{a_1}$ . That is, we have  $(v f^{a_1} + g^{a_1}) \cdot \gamma > 0$  but  $f^{a_1} \cdot \gamma < 0$ . Then, (A.3) implies that  $(\underline{v}^{a_1} f^{a_1} + g^{a_1}) \cdot \gamma \leq 0$ . Hence, we have

$$0 < (v f^{a_1} + g^{a_1}) \cdot \gamma = \underbrace{(\underline{v}^{a_1} f^{a_1} + g^{a_1}) \cdot \gamma}_{\leq 0} + \underbrace{(v - \underline{v}^{a_1}) f^{a_1} \cdot \gamma}_{\leq 0} \leq 0,$$

which leads to a contradiction.

(*Only-if statement*) Suppose that (A.3) is violated for some  $(a_1, \gamma) \in A_1 \times \Gamma$ , i.e.  $(\underline{v}^{a_1} f^{a_1} + g^{a_1}) \cdot \gamma > 0$  but  $f^{a_1} \cdot \gamma < 0$ . Let  $\xi > 0$  be small enough such that:

$$\max\{|\xi \gamma_1|, \dots, |\xi \gamma_n|\} < 1/n.$$

Consider two probability distributions  $\alpha_2, \alpha_2' \in \Delta(A_2)$ , where  $\alpha_2 \equiv \sum_{i=1}^n \frac{1}{n} \delta_{a_2^i}$ ,  $\alpha_2' \equiv \sum_{i=1}^n (\frac{1}{n} - \xi \gamma_i) \delta_{a_2^i}$ , and  $\delta_{a_2^i}$  denotes the Dirac measure on  $a_2^i \in A_2$ . Let  $\underline{\theta}$  be the smallest element in  $\Theta$ , which exists since  $\Theta$  is a complete lattice. By construction, when playing  $a_1$ , type  $\underline{\theta}$  sender strictly prefers  $\alpha_2$  to  $\alpha_2'$ . However, since  $f^{a_1} \cdot \gamma < 0$ ,  $u_1(\cdot, a_1, \alpha_2) - u_1(\cdot, a_1, \alpha_2')$  is strictly decreasing in  $\theta$ . Hence, condition

(A.1) is violated. □

Next, consider the linear operator  $\tau : \mathbb{R}^n \rightarrow \mathbb{R}^{n-1}$  with

$$\tau(w) \equiv (w_1 - w_n, \dots, w_{n-1} - w_n), \quad \forall w \in \mathbb{R}^n.$$

By construction,  $\tau(w) = 0$  if and only if  $w$  is a constant vector. In addition, for every  $\gamma \in \Gamma$  and  $w \in \mathbb{R}^n$ , we have  $w \cdot \gamma = \sum_{i=1}^{n-1} (w_i - w_n) \gamma_i = \tau(w) \cdot \gamma$ . Our next lemma provides a further characterization of condition (A.1) via the linear mapping  $\tau$ .

**Lemma A4.** *Suppose that  $u_1$  has the representation (A.2). Then,  $u_1$  satisfies condition (A.3) if and only if for every  $a_1 \in A_1$ , there exist  $\lambda, \mu \in [0, +\infty)$  with  $(\lambda, \mu) \neq (0, 0)$  such that*

$$\lambda \tau(f^{a_1}) = \mu \tau(\underline{v}^{a_1} f^{a_1} + g^{a_1}). \quad (\text{A.4})$$

PROOF. For every  $w \in \mathbb{R}^n$ , let us partition  $\Gamma$  into  $\Gamma^+(w), \Gamma^-(w), \Gamma^0(w)$ , such that  $w \cdot \gamma > 0$  (resp.,  $w \cdot \gamma < 0$ ) for every  $\gamma \in \Gamma^+(w)$  (resp.,  $\gamma \in \Gamma^-(w)$ ), and  $\Gamma^0(w) = \Gamma \setminus (\Gamma^+(w) \cup \Gamma^-(w))$ . Now we can equivalently state condition (A.3) as

$$\Gamma^+(\underline{v}^{a_1} f^{a_1} + g^{a_1}) \subset \Gamma^0(f^{a_1}) \cup \Gamma^+(f^{a_1}), \quad \forall a_1 \in A_1. \quad (\text{A.5})$$

(If statement) Pick any  $a_1 \in A_1$  and suppose there exist  $\lambda$  and  $\mu$  such that (A.4) holds. If either  $\lambda$  or  $\mu$  is 0, then since  $(\lambda, \mu) \neq (0, 0)$ , we have either  $\tau(f^{a_1}) = 0$  or  $\tau(\underline{v}^{a_1} f^{a_1} + g^{a_1}) = 0$ . In both cases, (A.5) is satisfied. If  $\lambda \mu \neq 0$ , then by (A.4) we have for every  $\gamma \in \Gamma^+(\underline{v}^{a_1} f^{a_1} + g^{a_1})$ ,

$$f^{a_1} \cdot \gamma = \tau(f^{a_1}) \cdot \gamma = \frac{\mu}{\lambda} \tau(\underline{v}^{a_1} f^{a_1} + g^{a_1}) \cdot \gamma = \frac{\mu}{\lambda} (\underline{v}^{a_1} f^{a_1} + g^{a_1}) \cdot \gamma > 0.$$

Hence,  $\gamma \in \Gamma^+(f^{a_1})$ .

(Only-if statement) Pick any  $a_1 \in A_1$  and consider the two  $n - 1$  dimensional vectors  $\tau(f^{a_1})$  and  $\tau(\underline{v}^{a_1} f^{a_1} + g^{a_1})$ . Suppose that the required  $\lambda$  and  $\mu$  do not exist. Then, there exists no  $\kappa \geq 0$  such

that  $\kappa\tau(f^{a_1}) = \tau(\underline{v}^{a_1} f^{a_1} + g^{a_1})$ . By Farkas' Lemma, there exists  $\tilde{\gamma} \equiv (\tilde{\gamma}_1, \dots, \tilde{\gamma}_{n-1}) \in \mathbb{R}^{n-1}$  such that

$$\tau(f^{a_1}) \cdot \tilde{\gamma} < 0 \text{ but } \tau(\underline{v}^{a_1} f^{a_1} + g^{a_1}) \cdot \tilde{\gamma} > 0.^{30}$$

Let  $\gamma \equiv (\tilde{\gamma}_1, \dots, \tilde{\gamma}_{n-1}, \tilde{\gamma}_n)$ , where  $\tilde{\gamma}_n \equiv -\sum_{i=1}^{n-1} \tilde{\gamma}_i$ . The construction of  $\tilde{\gamma}$  implies that  $\gamma \in \Gamma^+(\underline{v}^{a_1} f^{a_1} + g^{a_1})$  but  $\gamma \in \Gamma^-(f^{a_1})$ . This violates (A.5) and thus also violates (A.3).  $\square$

To conclude the proof of Proposition 1, we derive (4.12) from (A.4). According to the definition of  $\tau$ , Lemma A4 implies that for every  $(a_1, a_2) \in A_1 \times A_2$ ,

$$\lambda (f(a_1, a_2) - f(a_1, a_2^n)) = \mu \left[ (\underline{v}^{a_1} f(a_1, a_2) + g(a_1, a_2)) - (\underline{v}^{a_1} f(a_1, a_2^n) + g(a_1, a_2^n)) \right],$$

or, equivalently,

$$\mu g(a_1, a_2) = (\lambda - \mu \underline{v}^{a_1}) f(a_1, a_2) + h(a_1),$$

where

$$h(a_1) = \mu (\underline{v}^{a_1} f(a_1, a_2^n) + g(a_1, a_2^n)) - \lambda f(a_1, a_2^n).$$

On the one hand, if  $\mu \neq 0$ , let

$$\hat{v}(\theta, a_1) \equiv v(\theta, a_1) + (\lambda - \mu \underline{v}^{a_1})/\mu \text{ and } \hat{c}(\theta, a_1) \equiv c(\theta, a_1) + h(a_1),$$

which obtains representation (4.12). Note that by construction,  $\min_{\theta \in \Theta} \hat{v}(\theta, a_1) = \lambda/\mu \geq 0$ .

On the other hand, if  $\mu = 0$ , then we must have  $\lambda \neq 0$  and  $f(a_1, a_2) = h(a_1)/\lambda$ . In this case, let

$$\hat{f}(a_1, a_2) \equiv g(a_1, a_2), \hat{v}(\theta, a_1) \equiv 1 \text{ and } \hat{c}(\theta, a_1) \equiv c(\theta, a_1) + h(a_1)v(\theta, a_1)/\lambda,$$

which obtains representation (4.12).  $\square$

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<sup>30</sup>Farkas' Lemma implies the existence of  $\hat{\gamma} \in \mathbb{R}^{n-1}$  such that  $\tau(f^{a_1}) \cdot \hat{\gamma} \leq 0$  and  $\tau(\underline{v}^{a_1} f^{a_1} + g^{a_1}) \cdot \hat{\gamma} > 0$ . But given that  $\tau(f^{a_1}) \neq 0$ , if  $\tau(f^{a_1}) \cdot \hat{\gamma} = 0$ , there must exist  $\tilde{\gamma} \in \mathbb{R}^{n-1}$  close to  $\hat{\gamma}$  such that  $\tau(f^{a_1}) \cdot \tilde{\gamma} < 0$  and  $\tau(\underline{v}^{a_1} f^{a_1} + g^{a_1}) \cdot \tilde{\gamma} > 0$ .

## Appendix B - Not For Print

### B.1 Characterizing the Quasiconcavity-Preserving Property

In this Appendix, we provide a characterization of the quasiconcavity-preserving property based on the primitives of the model. We first introduce a strict version of the signed-ratio monotonicity condition in Quah and Strulovici (2012).

**Definition B1** (Strict Signed-Ratio Monotonicity). *A pair of functions  $\gamma_{\theta}^{a_1}, \gamma_{\theta'}^{a_1} : I \rightarrow \mathbb{R}$  obeys strict signed-ratio monotonicity (or SSRM) if*

(1) *for every  $i$  such that  $\gamma_{\theta}^{a_1}(i) < 0$  and  $\gamma_{\theta'}^{a_1}(i) > 0$ , we have*

$$-\frac{\gamma_{\theta}^{a_1}(i)}{\gamma_{\theta'}^{a_1}(i)} > -\frac{\gamma_{\theta}^{a_1}(j)}{\gamma_{\theta'}^{a_1}(j)} \quad \text{for every } j > i, \text{ and}$$

(2) *for every  $i$  such that  $\gamma_{\theta}^{a_1}(i) > 0$  and  $\gamma_{\theta'}^{a_1}(i) < 0$ , we have*

$$-\frac{\gamma_{\theta'}^{a_1}(i)}{\gamma_{\theta}^{a_1}(i)} > -\frac{\gamma_{\theta'}^{a_1}(j)}{\gamma_{\theta}^{a_1}(j)} \quad \text{for every } j > i.$$

The next result characterizes the quasiconcavity-preserving property in our setting, which is a straightforward extension of Theorem 1 in Quah and Strulovici (2012):

**Proposition B1.** *The receiver's payoff is quasiconcavity-preserving if and only if (i)  $\gamma_{\theta}^{a_1}$  satisfies SSCP for every  $(\theta, a_1) \in \Theta \times A_1$ , and (ii)  $\gamma_{\theta}^{a_1}$  and  $\gamma_{\theta'}^{a_1}$  obey SSRM for every  $a_1 \in A_1$  and every  $\theta, \theta' \in \Theta$ .*

PROOF. (*Only-if statement*) Suppose that the receiver's payoff is quasiconcavity-preserving, i.e.,  $\Gamma_{\tilde{\pi}}^{\theta}$  has the strict single-crossing property for every  $(a_1, \tilde{\pi}) \in A_1 \times \Delta(\Theta)$ . Then, (i) immediately follows by taking the degenerate distributions over  $\Delta(\Theta)$ . For (ii), pick any pair of functions  $\gamma_{\theta}^{a_1}$  and  $\gamma_{\theta'}^{a_1}$ . Suppose that  $\gamma_{\theta}^{a_1}(i) < 0$  and  $\gamma_{\theta'}^{a_1}(i) > 0$ . Let

$$\beta = \frac{-\gamma_{\theta}^{a_1}(i)/\gamma_{\theta'}^{a_1}(i)}{1 - \gamma_{\theta}^{a_1}(i)/\gamma_{\theta'}^{a_1}(i)},$$

so that  $\beta \in (0, 1)$  and  $\beta\gamma_{\theta}^{a_1}(i) + (1 - \beta)\gamma_{\theta'}^{a_1}(i) = 0$ . Since  $\beta\gamma_{\theta}^{a_1} + (1 - \beta)\gamma_{\theta'}^{a_1}$  has the strict single-crossing property, we have  $\beta\gamma_{\theta}^{a_1}(j) + (1 - \beta)\gamma_{\theta'}^{a_1}(j) > 0$  for all  $j > i$ . Given that  $\gamma_{\theta'}^{a_1}$  must satisfy SSCP and thus  $\gamma_{\theta'}^{a_1}(j) > 0$ , we can further obtain

$$\frac{1 - \beta}{\beta} = -\frac{\gamma_{\theta}^{a_1}(i)}{\gamma_{\theta'}^{a_1}(i)} > -\frac{\gamma_{\theta}^{a_1}(j)}{\gamma_{\theta'}^{a_1}(j)}.$$

Hence,  $\gamma_{\theta}^{a_1}$  and  $\gamma_{\theta'}^{a_1}$  must obey SSRM for every  $a_1 \in A_1$  and every  $\theta, \theta' \in \Theta$ .

(If-statement) Let  $\Theta \equiv \{\theta_1, \dots, \theta_K\}$ . We need to show that  $\forall \mu \equiv (\mu_1, \dots, \mu_K) \in [0, 1]^K$  such that  $\sum_{k=1}^K \mu_k = 1$ , the function  $\Gamma_{\mu}^{a_1} : I \rightarrow \mathbb{R}$  with  $\Gamma_{\mu}^{a_1}(i) \equiv \sum_{k=1}^K \mu_k \gamma_{\theta_k}^{a_1}(i)$  satisfies the strict single-crossing property. Since SSCP is preserved under positive scalar multiplication, and if  $\gamma_{\theta}^{a_1}$  and  $\gamma_{\theta'}^{a_1}$  obey SSRM then so do  $\beta\gamma_{\theta}^{a_1}$  and  $\gamma_{\theta'}^{a_1}$  for all  $\beta \geq 0$ , it suffices for us to show that  $\Gamma^{a_1} \equiv \sum_{k=1}^K \gamma_{\theta_k}^{a_1}$  satisfies SSCP.

Suppose that  $\Gamma^{a_1}(i) \geq 0$ . We want to show that  $\Gamma^{a_1}(j) > 0$  for every  $j > i$ . If  $\gamma_{\theta_k}^{a_1}(i) \geq 0$  for all  $k = 1, \dots, K$ , then we are done because each  $\gamma_{\theta_k}^{a_1}$  satisfies SSCP. Now suppose that  $\gamma_{\theta_k}^{a_1}(i) < 0$  for some  $\theta_k \in \Theta$ . In this case, let us partition  $\Theta$  into three subsets,  $\Theta^+$ ,  $\Theta^0$  and  $\Theta^-$ , such that  $\theta_{k'} \in \Theta^+$  if  $\gamma_{\theta_{k'}}^{a_1}(i) > 0$ ,  $\theta_{k'} \in \Theta^0$  if  $\gamma_{\theta_{k'}}^{a_1}(i) = 0$ , and  $\theta_{k'} \in \Theta^-$  if  $\gamma_{\theta_{k'}}^{a_1}(i) < 0$ . Hence, we have

$$\sum_{\theta_k \in \Theta^+ \cup \Theta^-} \gamma_{\theta_k}^{a_1} = \sum_{\ell=1}^L \gamma_{\ell}^{a_1},$$

where each function  $\gamma_{\ell} : I \rightarrow \mathbb{R}$  is a positive linear combination of at most two functions  $\gamma_{\theta_k}^{a_1}, \gamma_{\theta_{k'}}^{a_1}$  such that  $\theta_k, \theta_{k'} \in \Theta^+ \cup \Theta^-$ , and  $\gamma_{\ell}(i) \geq 0$  for all  $\ell = 1, \dots, L$ .

To complete the proof, it now suffices to show that for every  $\ell = 1, \dots, L$ , if  $\gamma_{\ell}^{a_1} = \alpha\gamma_{\theta_k}^{a_1} + \beta\gamma_{\theta_{k'}}^{a_1}$  for some  $\alpha, \beta > 0$  and  $\gamma_{\theta_k}^{a_1}, \gamma_{\theta_{k'}}^{a_1}$  such that  $\gamma_{\theta_k}^{a_1}(i) < 0$  and  $\gamma_{\theta_{k'}}^{a_1}(i) > 0$ , we would then obtain  $\gamma_{\ell}^{a_1}(j) > 0$  for every  $j > i$ . This is true because by SSRM, we have

$$\frac{\beta}{\alpha} \geq -\frac{\gamma_{\theta_k}^{a_1}(i)}{\gamma_{\theta_{k'}}^{a_1}(i)} > -\frac{\gamma_{\theta_k}^{a_1}(j)}{\gamma_{\theta_{k'}}^{a_1}(j)} \text{ for every } j > i,$$

and hence  $\gamma_{\ell}^{a_1}(j) = \alpha\gamma_{\theta_k}^{a_1}(j) + \beta\gamma_{\theta_{k'}}^{a_1}(j) > 0$ . □

## B.2 Strongly Monotone Equilibria

Theorems 1 - 3 in the main text provide sufficient conditions under which the sender uses a monotone strategy in every Nash equilibrium. As discussed in section 2, our notion of monotonicity can be strengthened in environments when  $A_1$  is multi-dimensional. This leads to the definitions of strongly monotone strategy and strongly monotone equilibrium:

**Definition B2.**  $\sigma_1$  is a strongly monotone strategy if  $\min_{a_1} \{supp(\sigma_1^\theta)\} \succeq \max_{a_1} \{supp(\sigma_1^{\theta'})\}$  for every  $\theta \succ \theta'$ . An equilibrium  $(\sigma_1, \sigma_2)$  is strongly monotone if  $\sigma_1$  is strongly monotone.

In words, a strategy is strongly monotone if a high type sender always plays a higher action than a low type. Plainly, strong monotonicity is strictly more demanding than monotonicity when  $A_1$  is multi-dimensional. In what follows, we use an example to illustrate why it is fundamentally more challenging to establish a result stating that all equilibria are strongly monotone.

Let  $\Theta = A_2 = \{0, 1, 2, 3\}$ , and  $A_1 = \{(0,0), (1,0), (0,1), (1,1)\}$ . All sets are endowed with the product order. Note that  $A_1$  is two-dimensional, and the sender's actions are only partially ordered. For all  $\theta \in \Theta$ ,  $a_1 = (a_{11}, a_{12}) \in A_1$  and  $a_2 \in A_2$ , the sender's payoff is given by

$$u_1(\theta, a_1, a_2) = \sqrt{a_2} - c(\theta, a_1),$$

where

$$c(\theta, a_1) = \begin{cases} 3a_{11} + 3a_{22} & \text{if } \theta = 0, \\ 0.9a_{11} + 2a_{22} & \text{if } \theta = 1, \\ 0.8a_{11} + a_{22} & \text{if } \theta = 2, \\ 0.2a_{11} + 0.2a_{22} & \text{if } \theta = 3. \end{cases}$$

The receiver's payoff is given by  $u_2(\theta, a_1, a_2) = 1$  if  $a_2 = \theta$ , and  $u_2(\theta, a_1, a_2) = 0$  otherwise. We leave the receiver's prior belief  $\pi$  unspecified as it plays no role.

In this example, the sender's payoff is *separable* and monotone-supermodular, which is sufficient to guarantee that she will use a monotone strategy in every equilibrium (Theorem 3). However, even the sender's payoff takes such a simple form, one cannot assert that all equilibria are strongly monotone. In particular, consider the following strategy profile: Type  $\theta = 0$  sender chooses  $a_1 =$

$(0, 0)$ , type 1 chooses  $a_1 = (1, 0)$ , type 2 chooses  $a_1 = (0, 1)$ , and type 3 chooses  $a_1 = (1, 1)$ . The receiver plays  $a_2 = 0$  if he observes  $a_1 = (0, 0)$ , 1 if he observes  $a_1 = (1, 0)$ , 2 if he observes  $a_1 = (0, 1)$ , and 3 if  $a_1 = (1, 1)$  is observed. One can check that this strategy profile constitutes a sequential equilibrium, in which every action of the sender is played with positive probability, and the players' incentives are strict. The sender's strategy is monotone but not strongly monotone, because the action  $(0, 1)$  taken by type 2 is not higher than the action  $(1, 0)$  taken by type 1.

In sum, the above example suggests that strong assumptions on the players' payoffs would need to be made if we want to further strengthen the robust monotonicity prediction about the sender's equilibrium strategies. In particular, the difficulty due to the incompleteness of the order on  $A_1$  cannot be easily bypassed even in the simplest settings where the sender's payoff is separable.

### B.3 Generalized Results with Infinite $A_2$

In this Appendix, we generalize our monotonicity results to cases where  $A_1$  is infinite. For simplicity, we shall assume that  $A_1 \subset \mathbb{R}^n$  with  $n \geq 1$  and it is a complete lattice with to the product order on the Euclidean space. With infinite  $A_1$ , a technical difficulty is that some of the actions in the support of  $\sigma_1^\theta$  can be suboptimal. Therefore, the notion of monotonicity in Definition 2 does not apply.

For every  $a_1 \in A_1$  and  $\alpha_1 \in \Delta(A_1)$ , let  $\Pr(\alpha_1 \succ a_1)$  be the probability that the realization of  $\alpha_1$  is strictly higher than  $a_1$ . To accommodate the above-mentioned technical difficulty, we introduce the following weaker version of monotonicity:

**Definition B3.**  $\sigma_1$  is an almost surely monotone strategy if for every  $\theta \succ \theta'$  and  $a_1 \in \text{supp}(\sigma_1^\theta)$ , we have  $\Pr(\sigma_1^{\theta'} \succ a_1) = 0$ . An equilibrium  $(\sigma_1, \sigma_2)$  is almost surely monotone if  $\sigma_1$  is almost surely monotone.

We establish the following result, which generalizes Theorem 1.

**Theorem B1.** *If  $|A_2| = 2$  and the sender's payoff is monotone-supermodular, then every Nash equilibrium is almost surely monotone.*

PROOF. The proof of Theorem 1 implies the following lemma.

**Lemma B1.** *Given the receiver's strategy  $\sigma_2$ , for every  $\theta \succ \theta'$  and  $a_1 \succ a'_1$ , if  $a'_1$  is a best response to  $\sigma_2$  for type  $\theta$ , then  $a_1$  is not a best response to  $\sigma_2$  for type  $\theta'$ .*

For every  $x \in \mathbb{R}^n$  and  $r > 0$ , let  $B(x, r)$  be the open ball around  $x$  with radius  $r$ . For every  $\theta \succ \theta'$  and  $a_1 \in \text{supp}(\sigma_1^\theta)$ , we have  $\sigma_1^\theta(B(a_1, r)) > 0$  for every  $r > 0$ . That is to say, there exists  $a'_1 \in B(a_1, r)$  such that  $a'_1$  is optimal for type  $\theta$ . Let  $a^r_1$  be the smallest element that is above every element in  $B(a_1, r)$ . Lemma B1 implies that  $\Pr(\sigma_1^{\theta'} \succ a^r_1) = 0$  for every  $r > 0$ . For every strictly positive decreasing sequence  $\{r_i\}_{i=1}^\infty$  with  $\lim_{i \rightarrow \infty} r_i = 0$ , we have:

$$\lim_{i \rightarrow \infty} \{a'_1 | a'_1 \succ a^{r_i}_1\} = \{a'_1 | a'_1 \succ a_1\} \text{ and } \{a'_1 | a'_1 \succ a^{r_i}_1\} \supset \{a'_1 | a'_1 \succ a^{r_j}_1\} \text{ for every } i > j.$$

The monotone convergence theorem implies that:

$$\Pr(\sigma_1^{\theta'} \succ a_1) = \Pr(\sigma_1^{\theta'} \succ \lim_{i \rightarrow \infty} a^{r_i}_1) = \lim_{i \rightarrow \infty} \Pr(\sigma_1^{\theta'} \succ a^{r_i}_1) = 0. \quad \square$$

The corresponding generalizations of Theorems 2 and 3 are similar and, therefore, omitted.