Who are we up against? Heterogeneous group contests with incomplete information

Vasudha Chopra[a,*], Hieu M. Nguyen[b], and Christian A. Vossler[c]

[a] *Department of Data Science, Economics and Business, Plaksha University, India 140306*
[b] *Department of Economics and Business, Southwestern University, Georgetown, TX 78626*
[c] *Department of Economics, University of Tennessee, Knoxville, TN 37996*

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[*]Correspondence should be directed to Vasudha Chopra, Department of Data Science, Economics and Business, Plaksha University, Alpha, Sector 101, IT City Rd, Sahibzada Ajit Singh Nagar, Punjab 140306. E-mail: veeechopra@gmail.com. Mobile: +919818777957. This paper reports research involving the collection of data on human subjects. Approval from the University of Tennessee Institutional Review Board was obtained, as protocol UTK IRB-19-05264-XM.

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Abstract: We study inter-group Tullock contests where there are two possible group types that are heterogeneous in the incentives they face, and players only know the probability their opponent is a particular group type. In the theory and complementary experiment, we compare three sources of heterogeneity – differences in cost-of-effort, prize value, and group size – and vary whether players have complete or incomplete information over the incentives facing the opponent. From the experiment, for the cost and value treatments, we find that incomplete information increases effort relative to uneven (i.e., asymmetric) complete information contests; for group size treatments, incomplete information has no effect. Observed effort is systematically higher than what a theory based on self-interest predicts; this is especially true for group size contests. An extended theory model that incorporates in-group altruism provides a potential explanation for major deviations between the data and standard theory predictions, including the finding that group-level effort increases with group size. Subjective probabilities over the opponent's type and bounded rationality provide potential explanations for a key result not predicted by the extended theory models.

JEL classifications : C70; C92; D74; D82; H41

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1. Introduction

The incentive structures induced by many organizations and institutions give rise to implicit or explicit inter-group competitions over prizes such as financial bonuses, government contracts, research grants, or reputation. The incentives motivating a competing group are often private information, and this has important implications for the effort devoted to winning the contest and, in turn, contest design. Consider for example the case where different law firms are competing to secure a client. How many people from the other firm are working on this? How talented are they? Will the firm pay the legal team a bonus if they land the client? In such environments, the contest designer, the client in this example, may strategically alter the incentive structure by offering different payments to different clients or controlling information on the characteristics of competing groups. These decisions logically alter team incentives. While a client may wish to motivate as much effort as possible, in other situations, the contest designer may instead wish to weaken effort incentives. This might characterize a case where the organization initiates the contest, and effort among competing teams within the organization is unproductive or otherwise the contest diverts resources away from more productive effort.

This paper uses theory and experiments to examine how behavior in potentially heterogenous group contests changes when players have incomplete information on the incentives facing their opponent. The present exploration thus seeks to not only deepen our understanding of strategic behavior in contests but also provides crucial insights for organizational leaders interested in designing systems that consider employee motivation and resource allocation. The theory and application focus on Tullock lottery contests, which along with other contest theory models have provided insight on a wide variety of settings, including lobbying firms competing for political resources, military conflicts between countries, competitions over patents and research awards, and sporting contests. A key feature of the Tullock contest is that the contest winner is determined by both costly effort expenditures and "luck."

Specifically, we model a contest between two groups that face two potential incentive structures ("types," hereafter). In the complete information setting, players know their own type as well as the opponent's type. In the incomplete information setting, players know their own group type, but only know the probability that the opponent is of a particular type. Players within a group are identical, group-level effort is an additive function of individual efforts (perfect substitutes), and individual efforts are not directly observable to teammates. Each member of the winning team receives an equal prize, regardless of individual effort. The value of the per-person prize does not vary with group size. We consider three potential sources of heterogeneity: cost-of-effort, prize value, and group size. The experimental design varies as treatments whether teams have complete or incomplete information on their opponent's type, and the source of heterogeneity.

We make three contributions to the literature. This is the first experiment to study the effect of incomplete information in a heterogeneous inter-group contest. Second, we evaluate whether the source of the potential advantage matters. While these sources of advantage have been studied in group contest settings to a limited degree, prior work has only examined them in isolation. Third, the experimental data and theoretical framework allow us to provide new insight on behavioral motives in inter-group contests. For instance, in contrast to the case where teams differ with respect to the prize value or cost-of-effort, the standard theory model based purely on self-interest predicts that group-level effort does not depend on group size. This, in turn, implies that incomplete information about group size is irrelevant. In contrast, the model of in-group altruism we consider predicts that both group size heterogeneity and incomplete information over the opponent's group size do impact group-level effort. These and other predictions that differ across candidate theoretical models provide a potential way to identify underlying behavioral motives.

Prior experimental studies examine the effects of uncertainty in lottery contests and all-pay auctions but have focused on competitions between individuals rather than groups (for recent surveys on contest experiments, see Dechenaux, Kovenock, and Sheremeta (2015) and Chowdhury, Esteve-González, and Mukherjee (2023)). In most of these studies, players are ex ante symmetric, but a parameter value (e.g., corresponding to per-unit effort cost) for an individual is determined by taking an independent draw from a common uniform distribution. For example, Brookins and Ryvkin (2014) find that incomplete information increases effort for advantaged (strong) players but decreases effort for disadvantaged (weak) players in a four-player contest. Boosey, Brookins, and Ryvkin (2017) introduce uncertainty in the number of players, finding that increasing the maximum number of competitors raises effort when the participation probability is low but decreases effort when it is high. Fallucchi, Renner and Sefton (2013) highlight the importance of information feedback in contests and find that providing information about own earnings and opponents' earnings and choices increases individual and group expenditures in lottery contests.

In his survey of the group contest literature, Sheremeta (2018) notes that few studies study contests between heterogeneous groups. As exceptions, Heap et al. (2015) assess the effects of providing teams with unequal endowments, which allows strong teams to contribute more towards winning the competition, and Bhattacharya (2016) examines contests between groups that differ in either the probability of winning or their effort cost. These investigations, including those with intra-group heterogeneity, generally find that strong players contribute relatively more effort.[1] A

[1] The same result is evident from experiments involving heterogeneous individual-level contests (see Dechenaux, Kovenock, and Sheremeta 2015).

few experiments examine heterogeneity in group contests in the form of different group sizes. Rapoport and Borenstein (1989) and Kugler, Rapoport and Pazy (2010) examine contests between three- and five-player groups and find that even in cases where theory predicts the smaller team should expend more collective effort, larger groups are instead more likely to win. For our group size treatments, like Abbink et al. (2010) and Ahn, Isaac, and Salmon (2011) who study contests between an individual and a group of four, the value of the prize for each player on the winning team does not depend on group size. This design choice ensures that a group size difference is the only potential source of advantage.

Our theoretical framework builds on Tullock's (1980) canonical model, Katz, Nitzan, and Rosenberg (1990) who model a group Tullock contest setting with inter-group heterogeneity, and Malueg and Yates (2004) who study individual-level contests with incomplete information over the prize value. Prior theoretical work on group contests with incomplete information is limited. Eliaz and Wu (2018) focus on uneven all-pay auctions, Fu, Lu, and Pan (2015) examine incomplete information over cost-of-effort in a generalized Tullock contest, Brookins and Ryvkin (2016) study group-level private information over cost-of-effort, and Boosey, Brookins, and Ryvkin (2019) investigate group contests with unknown group size. Additionally, in their recent survey, Chowdhury, Esteve-González, and Mukherjee (2023) emphasize the significance of how information availability about various aspects of contests influences the incentive to compete. They also note the scarcity of studies that theoretically explore the effects of different types of information on effort in contests.

We add to this theory literature by incorporating behavioral motives in inter-group contest models that predict effort levels that exceed predictions from the standard economic model of self-interest. This is motivated by the stylized fact of "overbidding" in the Tullock contest literature, and related literatures such as the case of all-pay auctions (e.g., Cason, Sheremeta, and Zhang 2012; Leibbrandt and Sääksvuori 2012). Studies such as Lugovskyy, Puzzello, and Tucker (2010) highlight that overbidding is pervasive and cannot simply be mitigated through additional game repetitions or reputational factors. On a related note, Sheremeta (2013) identifies factors that may reduce overbidding in Tullock contests, such as using earned money instead of house money, making small periodic payments rather than a lump sum, and allowing communication. Despite inclusion of these design characteristics in many contest experiments, overbidding has persisted.

Moreover, the literature highlights that there may be one or more behavioral motivations for overbidding, and they might even be inter-dependent (Sheremeta 2010; Mago, Samek and Sheremeta 2016). Motivated by this evidence, when designing the experiment, we considered a standard model along with one that incorporates in-group altruism. In response to prior feedback, we also consider the extent to which out-group hostility and a non-monetary utility of winning may reconcile theory and data. While Sheremeta (2018) highlights these motivations in his review of the group contest literature, evidence in support of these motivations come from individual-level contests and non-contest experiments.[2]

In the experiment, we find incomplete information increases effort relative to complete information "uneven" contests, i.e., contests between groups of different types, with known cost-of-effort or prize value differences. However, regardless of the potential source of advantage, effort in incomplete information contests is equivalent to that from "even" contests where both groups are knowingly competing against the same group type. Consistent with standard theory, when the source of the advantage is either a lower cost-of-effort or a higher prize value, we find

[2] Sheremeta (2018) also discusses relative payoff maximization (captured by parochial altruism in a group contest setting) and cognitive limitations as possible explanations for over-expenditure of effort. Relative payoff maximization is captured by a model of parochial altruism in this group contest setting. While we do not formally model bounded rationality, we consider the effects of cognitive ability through a proxy measure (i.e., GPA) in the data analysis.

that effort is higher for advantaged (strong) relative to disadvantaged (weak) groups. Contrary to self-interest theory's prediction of a null effect, group-level effort increases dramatically with group size, and a three-fold group size advantage results in higher effort compared to a three-fold cost or prize value advantage. Extending the theory to include in-group altruism and potentially a non-monetary utility of winning improves the alignment between theory and data.

2. Theoretical Framework

In this section we model a heterogenous group Tullock contest under complete and incomplete information. The model builds on Tullock's (1980) canonical model of a rent-seeking contest, Katz, Nitzan, and Rosenberg (1990) who model a group Tullock contest setting with inter-group heterogeneity, and Malueg and Yates (2004) who study individual contests with incomplete information over player types. In Section 5 we will expand the model to include motivates other than self-interest.

Consider a contest between two groups. Group g consists of n_g risk-neutral players, and groups compete to win a prize. Regardless of their individual actions, the value of the prize to each player on the winning team is v_g, and there is no prize for the losing team. This may, for instance, characterize a setting where the group prize is a (local) public good that is non-excludable and non-rival in consumption. All players in both groups simultaneously and independently expend effort x_{ig} at a (constant) per-unit cost of c_g. Player efforts within a group are perfect substitutes, such that group-level effort, X_g, is simply the sum of player efforts, i.e., $X_g = \sum_{i=1}^{n_g} x_{ig}$. The probability of winning, p_g, depends on the relative effort of the competing teams according to the contest success function (CSF) of Tullock (1980) for the standard lottery case:

[1] $$p_g = \begin{cases} \frac{X_g}{X_g + X_{-g}} & \text{for } X_g + X_{-g} > 0 \\ \frac{1}{2} & \text{for } X_g = X_{-g} \end{cases}$$

When both teams expend the same effort, each has an equal probability of winning. Otherwise, the team that exerts more effort has a higher probability of winning.

Let $g \in \{S, W\}$ denote the group's type. A type S or "strong" group has a lower per-unit cost of effort ($c_S < c_W$), is incentivized by a higher per-person prize value ($v_S > v_W$), or has more team members ($n_S > n_W$) than a type W or "weak" group.[3] In most cases, theory predicts that group-level effort in a strong team will exceed that of a weak group, regardless of their opponent's type. We will limit the analysis here to settings where there is at most one source of advantage between competing groups.[4]

We consider two information conditions. In the complete information condition, each player has perfect knowledge of their own group's type as well as their opponent's type. In the incomplete information condition, players know their own group's type but only know whether the other group is type S with probability r.

2.1. Complete information

When all players know the parameters characterizing their own group as well as their opponent, the expected payoff for a representative player is (assuming players are symmetric):

[2] $$\pi_{ig} = p_g v_g - c_g x_{ig}$$

A risk-neutral individual chooses effort x_{ig} to maximize [2], yielding the first-order condition:

[3] This descriptor is admittedly imperfect as, in the case of group size, being in a larger group can easily weaken the incentives for individuals to expend costly effort.

[4] The theory logically extends to settings where a team has an advantage in multiple dimensions. Ambiguity in the various comparisons of course arises if a group holds an advantage in one dimension, but a disadvantage in another.

[3] $$\frac{X_{-g}}{(X_g+X_{-g})^2} v_g - c_g \ = 0.$$

The maximization problem for a representative player from the opposing team $-g$ is symmetric, giving rise to the first-order condition:

[4] $$\frac{X_g}{(X_{-g}+X_g)^2} v_{-g} - c_{-g} \ = 0.$$

The two first-order conditions include only group-level efforts, implying the theory is silent about individual effort. Assuming an interior solution, the pure-strategy Nash equilibrium is attained by solving [3] and [4] simultaneously for X_g and X_{-g}. Equilibrium effort for a type g group is:

[5] $$X_g^* = \frac{c_{-g} v_g^2 v_{-g}}{\left(c_g v_{-g} + c_{-g} v_g\right)^2}$$

In terms of group-level effort, this equilibrium is unique. In terms of individual effort, there is one symmetric equilibrium and multiple asymmetric equilibria in which the sum of the individual efforts equals the group-level equilibrium (Baik 1993). This is the result of assuming constant marginal effort costs and the same prize value to each team member. Clear from [5] is that equilibrium effort is not a function of group size.

Table 1 presents equilibria for complete information contests. For clarity, when presenting equilibria, we drop the subscripts on parameters held fixed across competing groups. Complete information contests where both groups are of the same type are referred to as "even" contests; otherwise, contests between different types are "uneven."

When both teams have either a low cost parameter or a high value parameter, group effort is strictly higher when compared to an even contest between two teams facing either high costs or a low prize value. Moreover, in an uneven contest with either cost or value heterogeneity, a strong team exerts more effort than their opponent. Interestingly, a weak team expends relatively lower effort when in an uneven relative to an even contest. This is a discouragement effect that arises because playing against a strong opponent lowers the chance they win in equilibrium, which serves to disincentivize effort (Fonseca 2009, Kimbrough et al. 2014).

Table 1. Equilibrium effort in *complete* information contests, self-interest model

Source of heterogeneity	Contest type	Equilibrium effort
Cost-of-effort	Uneven	$(X_S^*, X_W^*) = \left(\frac{vc_W}{(c_S+c_W)^2}, \frac{vc_S}{(c_S+c_W)^2}\right)$
	Even	$(X_S^*, X_S^*) = \left(\frac{v}{4c_S}, \frac{v}{4c_S}\right)$; $(X_W^*, X_W^*) = \left(\frac{v}{4c_W}, \frac{v}{4c_W}\right)$
Prize Value	Uneven	$(X_S^*, X_W^*) = \left(\frac{v_W v_S^2}{c(v_S+v_W)^2}, \frac{v_S v_W^2}{c(v_S+v_W)^2}\right)$
	Even	$(X_S^*, X_S^*) = \left(\frac{v_S}{4c}, \frac{v_S}{4c}\right)$; $(X_W^*, X_W^*) = \left(\frac{v_W}{4c}, \frac{v_W}{4c}\right)$
Group Size	Uneven	$(X_S^*, X_W^*) = \left(\frac{v}{4c}, \frac{v}{4c}\right)$
	Even	$(X_S^*, X_S^*) = \left(\frac{v}{4c}, \frac{v}{4c}\right)$; $(X_W^*, X_W^*) = \left(\frac{v}{4c}, \frac{v}{4c}\right)$

Notes: An "uneven" contest refers to a case where a strong (S) group plays a weak (W) group. The strong team has either a lower cost of effort (i.e., $c_S < c_W$), higher prize value ($v_S > v_W$), or larger group size (i.e., $n_S > n_W$) relative to a weak team. In an "even" contest, both groups are of the same type.

As mentioned earlier, the self-interest model equilibrium is independent of group size, indicating identical efforts from groups of any size, i.e., $X_S^* = X_W^*$, for both even and uneven contests in the case of group-size heterogeneity. At least when viewed through the lens of this model, the "strong" versus "weak" labels may seem potentially misleading in the case of group size heterogeneity. However, we will later consider theory models that predict larger groups exert higher group-level effort.

2.2. Incomplete information

In the incomplete information setting, players only know their opponent will either be strong with probability r or weak with probability $1-r$. The maximization problem is:

$$[6] \qquad \max_{x_{ig}} U_{ig} = \left(r \cdot p_{g,S} + (1-r)p_{g,W}\right)v_g - c_g x_{ig}$$

$$= \left(r \frac{X_g}{X_g+X_S} + (1-r)\frac{X_g}{X_g+X_W}\right)v_g - c_g x_{ig}$$

The associated first-order condition is:

$$[7] \qquad \left(r \frac{X_A}{(X_g+X_S)^2} + (1-r)\frac{X_D}{(X_g+X_W)^2}\right)v_g - c_g \ = 0.$$

This yields two equations based on whether $g = S$ or $g = W$. Here, we solve for the equilibrium when $r = \frac{1}{2}$, which coincides with the experiment. Focusing on the cost heterogeneity case, the (pure-strategy) symmetric Bayesian-Nash equilibrium effort for a team of type g is:

$$[8] \qquad X_g^{**} = \frac{v}{c_g}\left(\frac{4\frac{c_S}{c_W} + \left(1+\frac{c_S}{c_W}\right)^2}{8\left(1+\frac{c_S}{c_W}\right)^2}\right).$$

Table 2 presents the equilibrium for the incomplete information condition for $r = \frac{1}{2}$, for cases where competing groups potentially vary with respect to effort cost, prize value, or group size.[5] We solve for the equilibrium in the general case of $0 < r < 1$ in the appendix.

[5] For the self-interest model, the group contest equilibria are identical to those based instead on a contest among individuals. It follows that similar results can be found in Malueg and Yates (2004), Fey (2008), and Serena (2022) for the $r = \frac{1}{2}$ case.

Table 2. Equilibrium effort in *incomplete* information contests, self-interest model

Source of heterogeneity	Equilibrium effort
Cost-of-effort	$X_S^{**} = \frac{v}{c_S}\left(\frac{4\frac{c_S}{c_W}+\left(1+\frac{c_S}{c_W}\right)^2}{8\left(1+\frac{c_S}{c_W}\right)^2}\right)$; $X_W^{**} = \frac{v}{c_W}\left(\frac{4\frac{c_S}{c_W}+\left(1+\frac{c_S}{c_W}\right)^2}{8\left(1+\frac{c_S}{c_W}\right)^2}\right)$
Prize Value	$X_S^{**} = \frac{v_S}{c}\left(\frac{4\frac{v_W}{v_S}+\left(1+\frac{v_W}{v_S}\right)^2}{8\left(1+\frac{v_W}{v_S}\right)^2}\right)$; $X_W^{**} = \frac{v_W}{c}\left(\frac{4\frac{v_W}{v_S}+\left(1+\frac{v_W}{v_S}\right)^2}{8\left(1+\frac{v_W}{v_S}\right)^2}\right)$
Group Size	$X_S^{**} = \frac{v}{4c}$; $X_W^{**} = \frac{v}{4c}$

Notes: The equilibrium effort of strong and weak teams are denoted by X_S^{**} and X_W^{**}, respectively. A strong team has either a lower cost of effort (i.e., $c_S < c_W$), higher prize value ($v_S > v_W$), or larger group size (i.e., $n_S > n_W$) relative to the weak team. Equilibria correspond with $r = \frac{1}{2}$, i.e., that there is a 50% chance the opponent is a strong team.

Conditions for the existence and uniqueness of the equilibrium follow from the results of Brookins and Ryvkin (2016) for group contests, and the closely related theory of individual contests (e.g., Ewerhart and Quartieri 2020). As in the case of complete information, a strong team is predicted to exert more effort relative to a weak team which, in turn, means a strong team is more likely to win (as there is a chance their opponent is weak). Next, we summarize the predicted differences in effort between complete and incomplete information contests through three propositions. Proofs are provided in the appendix. For ease of exposition, we define "contest-level effort" as the sum of effort across both competing teams. Further, as players in an incomplete information contest do not know whether the contest is "even" or "uneven," we will only use these labels when referring to complete information contests.

Proposition 1: For group contests with potential cost or prize value heterogeneity, expected contest-level effort for an incomplete information contest is: (a) *higher* relative to an uneven contest; and (b) *lower* relative to the average even contest.

Proposition 2: For group contests with potential group size heterogeneity, incomplete information has no effect on effort.

Proposition 3: For group contests with potential cost or prize value or group size heterogeneity, expected contest-level effort is equal under incomplete and complete information when $r = \frac{1}{2}$.

In the case of cost or value heterogeneity, relative to an uneven contest, both strong and weak teams increase effort under incomplete information. This is because the team does not know for sure that their opponent is weak and increases effort accordingly. The effect of incomplete information increases with the difference in the cost or value parameter. As a result, contest-level effort is strictly higher under incomplete information when compared to complete information. This result holds more generally for $0 < r < 1$ (see appendix).

For an even contest, both teams exert equal effort, and effort is higher when both teams either face a low cost or high value parameter. With incomplete information, a team does not know the opposing team's type. Players in both groups suspect that they are playing against a strong opponent with a probability less than 1, and this lowers effort relative to the complete information case. This is due to a discouragement effect (Fonseca 2009; Kimbrough et al. 2014). This result holds more generally for $0 < r < 1$ (see appendix).

In complete information contests, group size has no effect on group-level effort in either uneven or even contests. It logically follows that introducing uncertainty over the size of the opponent's group also has no effect.

When considering the expected contest-level effort, unconditional on contest type, the differential effects of incomplete information (when present) relative to uneven and even contests will counteract. When $r = \frac{1}{2}$, the effects completely offset. Otherwise, for the case of cost or value heterogeneity, contest-level effort is higher with incomplete information when $r < \frac{1}{2}$, and lower when $r > \frac{1}{2}$. We support these results in the appendix. Serena (2022) provides a more formal proof of this result for a related setting.[6]

3. Experimental Design

In an experiment session, participants are randomly placed into groups, and then paired with a competing group. Players are randomly rematched into groups prior to each of 20 independent decision rounds. This design choice is intended to provide a better test of the theory, which is of a one-shot game. To minimize possible end-of-game effects, participants do not know in advance the total number of rounds. In a decision round, the task of each player is to decide how many points ("effort" in the theory) to contribute to a "group project." Contributing points comes at a constant per-unit cost, and participants can select any integer amount between 0 and 50 points (inclusive). To avoid negative earnings, in each decision round a participant receives a "fixed income" sufficient to cover any effort costs. After all choices are made, the points contributed are added up for both groups, and the probability a group wins is determined by equation [1]. Each member of the winning group receives an identical monetary prize.

[6] Serena (2022) studies the closely related question of when it is optimal for a contest designer, who wishes to maximize effort, to reveal information on the contestant types in a contest between two individuals. As group-level effort is not a function of group size, Serena's results readily apply to contests between groups rather than individuals.

We employ a 2 x 3 between-subjects design that varies the information condition (complete or incomplete information) and the potential source of advantage (cost, value, or group size). Table 3 summarizes the experiment parameters. As in the theory, we characterize a group as either strong or weak. Regardless of the potential source of advantage, a weak group has three players (i.e., $n_W = 3$), and players therein can contribute at a cost of 1 lab dollar per point ($c_W = 1$) in attempt to win a prize that yields a payoff of 50 lab dollars per player ($v_W = 50$). To construct strong teams, we vary the relevant parameter by a factor of three: $c_S = 1/3$, $v_S = 150$, or $n_S = 9$.

In each decision round, a team has a 50% chance of being strong, and determinations are made independently for each team. For example, in a cost treatment, each group has a 50% chance of facing a 1 lab dollar effort cost and a 50% chance of a 1/3 lab dollar effort cost. Overall, this means that there is a 25% chance that both teams are weak, a 25% chance that both are strong, and a 50% chance of a contest between a weak and a strong team.[7] In the complete information condition, players have full knowledge of the incentives (cost, value, and group size) facing members of their team as well as the competing team. In the incomplete information condition, players have full information on the parameters facing their own team only. They do know that the other team has a 50% chance (i.e., $r = 1/2$) of being strong, and that the status of each group is determined independently. In other words, when a player is on a strong team, this provides her with no additional information on the type of the competing group. Consistent with the theory, under incomplete information players are uncertain about a single parameter facing their opponent but know the values for the other two parameters.

[7] For the group size treatments, we hard-coded possible sets of contests that could take place in the same round based on the number of participants in a session. The probability a specific contest type occurs can then be controlled by assigning probabilities to the possible contest sets.

Table 3. Experiment parameters

Source of heterogeneity	**Group type**	**Cost**	**Value**	**Group size**
Cost-of-effort	Strong	$c_S = 1/3$	$v = 50$	$n = 3$
	Weak	$c_W = 1$	$v = 50$	$n = 3$
Prize Value	Strong	$c = 1$	$v_S = 150$	$n = 3$
	Weak	$c = 1$	$v_W = 50$	$n = 3$
Group Size	Strong	$c = 1$	$v = 50$	$n_S = 9$
	Weak	$c = 1$	$v = 50$	$n_W = 3$

Table 4. Theoretical predictions and observed group-level effort

		(1) Self-Interest model		**(2) In-group altruism model ($\alpha = 1$)**		**(3) Observed**	
Source of heterogeneity	Contest Type	X_S	X_W	X_S	X_W	X_S	X_W
Cost-of-effort	Uneven	28.13	9.38	84.38	28.13	75.04	20.10
Cost-of-effort	Even	37.50	12.50	112.50	37.50	80.80	49.43
Cost-of-effort	Incomplete information	32.81	10.94	98.44	32.81	89.27	42.49
Prize Value	Uneven	28.13	9.38	84.38	28.13	70.69	27.05
Prize Value	Even	37.50	12.50	112.50	37.50	76.84	43.73
Prize Value	Incomplete information	32.81	10.94	98.44	32.81	84.85	51.69
Group Size	Uneven	12.50	12.50	84.38	28.13	119.57	41.14
Group Size	Even	12.50	12.50	112.50	37.50	128.50	51.91
Group Size	Incomplete information	12.50	12.50	98.44	32.81	118.49	40.26

Notes: X_S and X_W refer to effort for strong and weak groups, respectively. The self-interest model predictions are calculated using the equilibria presented in Table 1. The in-group altruism model predictions are calculated from the formulas in Table A.1 and A.2 in the appendix, using an altruism parameter motivated by both prior research and the experiment data (see Section 5.4).

3.1. Theoretical predictions and testable hypotheses

Column (1) in Table 4 presents theory point predictions for uneven, even, and incomplete information contests, respectively, derived from the self-interest model.[8] As evident from the predictions, the experimental design lends itself to testing group contest theories in several ways. Consistent with the theory, incomplete information is expected to alter effort in cost and value treatments (Proposition 1), but not in group size treatments (Proposition 2). Facing a higher prize value or lower cost-of-effort induces higher effort. In fact, given the three-fold difference in the heterogeneous parameter (e.g., $c_S/c_W = 3$) for both cases, theory predicts a strong team will expend exactly three times more effort than a weak team.[9] It follows that expected effort for cost and value treatments should be identical. On the other hand, being in a larger group is expected to have no effect on group effort. As such, overall effort is predicted to be lowest for the group size treatments. We summarize the main testable hypotheses below.

H1. For cost and value treatments, effort in an incomplete information contest is: (a) higher than in an uneven contest; (b) lower than in an even contest; and (c) equal to effort in the average complete information contest.

H2. For the group size treatments, effort does not vary across the three contest types (uneven, even, and incomplete).

H3. There are no differences in effort across contests with potential cost or value heterogeneity.

H4. Effort is higher in the value or cost treatments relative to group size treatments.

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[8] Using the results in Malueg and Yates (2004), the experiment parameters satisfy the conditions for the existence and uniqueness of the equilibrium.

[9] We will later consider an alternative theory model that incorporates in-group altruism. For this model, and an altruism parameter of $\alpha = 1$ (which we will show in Section 5.2 provides a good fit between theory and the data), group-level effort is also predicted to be three times higher for a strong team relative to a weak one.

H5. (a) For cost and value treatments, effort is higher for strong versus weak groups. (b) For group size treatments, effort is the same for strong and weak groups.

The first two hypotheses follow directly from the three Propositions, and tests of the first four hypotheses are unique to this study. While effort differences across strong and weak groups (tied to Hypothesis 5) have been previously evaluated under complete information, our experimental design provides an additional test under incomplete information as well as across multiple sources of heterogeneity.

3.2. Pilot experiment and power analysis

To help inform the experimental design, a pilot experiment was conducted using the cost treatment with incomplete information. Participants were drawn from the same population and experimental procedures closely followed the final protocols described later.[10] Based on a power analysis using the pilot data, we settled on a plan to enroll 360 participants in sessions of approximately 18 people. In particular: 54 participants per treatment for the four treatments involving cost and value heterogeneity; and 72 participants per treatment for the two group size treatments. Having additional participants in the group size treatments helps to counteract the fact that these treatments generate relatively fewer group-level observations. Target sample sizes, and associated minimum detectable effect sizes, are motivated by predictions from a theory model of in-group altruism, discussed in Section 5, with an altruism parameter of $\alpha = 1$.[11]

[10] For this reason, we include data from the pilot in the analysis.

[11] For this altruism parameter, predictions for all three sources of advantage are identical. The in-group altruism model, along with this parameter choice, were motivated by the literature. In the Abbink et al. (2010) experiment, the four-person teams in no-punishment treatments expend 1,035 points on average, which is 4.1 times (implying $\alpha \approx 1$) the prediction of standard theory (250 points). Bhattacharya (2016), with three-person groups, finds that group-level effort averages 689 in even contests, and effort for strong and weak teams in uneven contests average 951 and 555, respectively. These effort levels are 4.3 to 5.5 times standard theory predictions, and in all cases imply $\alpha > 1$. Chen

A power analysis based on the planned sample sizes, 80% power, a 5% significance level, and two-sided tests, yields the following minimum detectable effect sizes.[12] We can detect a minimum treatment effect size of 9.4 units of group-level effort when testing Hypothesis 1 for the group size treatments, and an effect size of 8.4 when testing the same hypothesis based on either the cost or value treatments. For tests of Hypothesis 2, these figures are 8.9 and 8.4, respectively. Tests of Hypothesis 3 are powered to detect somewhat smaller differences, given that data from even and uneven contests are pooled (7.7 for group size treatments, and 7.0 for value and cost treatments). For Hypothesis 4 and Hypothesis 5, minimum detectable effect sizes range from 7.0 to 10.5, and from 9.5 to 11.0, respectively. Power calculations are only approximations as the true underlying outcome distributions are unknown. However, they provide reasonable indications of how large the true treatment effects need to be to be detected with the experimental design (with a high probability). In other words, any "null" findings should not be construed as evidence that the true effect is zero, but instead that the effect is most likely smaller than the stated minimum detectable effect sizes.

3.3. Experimental procedures

A typical experimental session proceeds as follows. Participants are randomly assigned an ID number and a computer station in the laboratory. The same moderator reads instructions aloud, hard copies of which are provided to participants, and follows protocols described in the consent form. Participants enter all decisions on personal computers. The experiment was programmed

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and Li (2009) assume in their theory that individuals place the same weight on their group members' payoffs as their own, which is consistent with the assumption $\alpha = 1$.

[12] The minimum detectable effect sizes are based on an assumed analysis where group-level efforts observed in the same decision round are freely correlated (i.e., linear regressions with clustering by round). In the analysis presented later, we further allow for group-level efforts to be serially correlated. As the differences in estimated standard errors when using one versus two-way clustering are sufficiently small, the reported effect sizes remain informative for the data analysis.

and conducted using the software z-Tree (Fischbacher 2007). Prior to the group contest experiment participants complete a (paid) risk elicitation task of the sort popularized by Holt and Laury (2002). The outcome of this task is not revealed until the end of the session. After reading instructions for the group contest experiment, participants take an incentivized quiz designed to evaluate and educate participants on earnings calculations and procedures. Participants then proceed through one unpaid training round and can ask questions prior to the paid rounds.

For complete information treatments, the decision screen displays all three parameters (cost, value, group size) in effect for the participant's group as well as the opponent group. For incomplete information treatments, the same information is provided except for one parameter in effect for the opponent group; for this parameter, two possible values are displayed, and each has a 50% chance of being the actual value. After all participants enter their effort decisions, a summary screen reveals which team won, total effort for the participant's group, and earnings for the decision round. Participants do not see the individual efforts of their team members, nor do they receive any direct information on the choices of their opponent. Further, in incomplete information contests, participants do not learn their opponent's type at the end of each round. Participants earn money based on the outcome in each of the 20 paid decision rounds. The experiment concludes with a demographic questionnaire. Representative instructions and the questionnaire are in the appendix.

3.4. Participants

Twenty-one experiment sessions were conducted during the summer and fall of 2019 as well as fall of 2020 in a designated experimental economics laboratory at the University of

Tennessee, Knoxville.[13] Including the pilot, we have data from 360 participants.[14] Undergraduate students were recruited from a large existing database that had previously registered to receive invitations for economics experiments. Participants were not allowed to attend more than one session of the experiment. Earnings were denominated in "lab dollars" and exchanged for U.S. dollars at an announced exchange rate. As theory predicted earnings in the value treatments to be considerably higher, we used an exchange rate of 120-to-1 for the value treatments, and 90-to-1 for the remaining treatments. The experiment lasted approximately 50 minutes. On average participants earned $17.91 for the session, which includes earnings of $2.51 from the risk elicitation task and $0.86 from the quiz.

Table 5 describes the experiment data. Overall, 44% of participants are female, 56% had participated in a prior economics experiment, and 47% can be characterized as risk averse based on the incentivized risk elicitation task. The average score on our instructions quiz is about 86%. Sixty percent of participants answered all quiz questions correctly, 27.5% answered three correctly, and the remainder answered 2 or fewer questions correctly. Responses from the post-experiment questionnaire suggest that the vast majority (88%) felt they were sufficiently compensated. In response to a Likert-scale question that ranged from "1" ("poorly understood") to "5" ("well understood"), the vast majority (89%) selected a 4 or 5, indicating a strong self-assessment of comprehension.

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[13] Two of the sessions were conducted during the COVID-19 pandemic. The experimental procedures were identical aside from the safety protocols (social distancing and facemasks) in place. While there are not enough data to reliably test whether behavior differed in these two sessions, excluding this data from the analysis does not alter any of the main conclusions (see tables B.1 and B.2 in the appendix).

[14] Given the number of participants (360) and decision periods (20), there are 7200 individual-level observations: 2160 each from the cost and value treatments, and 2880 from the group size treatments. There are 1988 group-level observations: 720 each from the value and cost treatments, and 548 from the group size treatments. The latter figure reflects the mix of large and small groups formed across the group size treatment sessions. Due to variations in participant show-up rates, there are 42 participants in the complete information cost treatment and 66 participants in the incomplete information cost treatment. Revising our power calculations based on these realized sample sizes has only a negligible effect. We met exactly our sample size targets for the other treatments.

Table 5. Description of data

Variable name	Description	Mean (std dev)
Dependent Variables		
Group Effort	Total points contributed by all group members	74.90 (45.77)
Probability of Winning	Calculated as a function of own and opponent group effort, using equation [1]	52.42 (22.85)
Individual Effort	Points contributed by the participant, 0 to 50 points	18.04 (16.07)
Effort Variance	Squared deviation of a participant's contribution relative to the mean contribution within the group	145.81 (211.14)
Zero Effort	= 1 if participant contributed zero points; 0 otherwise	0.21 (0.41)
Experimental treatment Variables		
Strong	= 1 for "strong" group type; 0 for "weak"	0.56 (0.50)
Incomplete	= 1 for incomplete information treatments; 0 otherwise	0.53 (0.50)
Even	= 1 for even complete information contests; 0 otherwise	0.24 (0.43)
Cost	= 1 for cost treatments; 0 otherwise	0.30 (0.46)
Value	= 1 for value treatments; 0 otherwise	0.30 (0.46)
Group	= 1 for group size treatments; 0 otherwise	0.40 (0.49)
Additional Control Variables		
Risk Averse	= 1 if participant selected safe option at least six times in Risk Elicitation task; 0 otherwise	0.47 (0.50)
Experience	=1 if the participant had partaken in a prior economics experiment; 0 otherwise	0.56 (0.50)
Female	= 1 if participant is female; 0 otherwise	0.44 (0.51)
Decision Round	Decision round in the experiment, 1 to 20	10.50 (5.77)
GPA	Participant GPA, recorded as midpoint of chosen interval	3.29 (0.49)
$Loss_{t-1}$	= 1 for players who were on a losing team in the prior round (t-1), 0 otherwise	0.46 (0.50)
Group $Effort_{t-1}$	Total points contributed by all members of the participant's group in the prior round (t-1)	75.37 (45.93)

Notes: Means and standard deviations are calculated based on the experiment panel data with individual-level observations.

4. Results

Column (3) in Table 4 presents the observed group-level efforts by group type (strong or weak), source of heterogeneity (cost, value, group size), and contest type. Consistent with the theory, and testable hypotheses, we focus on three contest types. The "uneven" and "even" types are complete information contests between a strong and a weak team, and two teams of the same type, respectively. While the incomplete information contests may also be described as "uneven" and "even", players are never aware of their opponent's type, and theory predicts the same effort regardless of the reality of the situation.

The summary statistics in columns (1) and (3) of Table 4 convey the following insights. First, in all cases, actual effort far exceeds what is predicted by the self-interest model. For cost-of-effort and prize value treatments, effort is two to four times higher, depending on the comparison, and is three times higher on average. For the group-size treatments, effort for strong teams exceeds self-interest theory predictions by an order of magnitude and is roughly three times higher relative to weak teams. Second, even though standard theory predicts effort is invariant to group size, effort in the group size treatments is generally higher, especially for strong groups, relative to cost and value treatments. Third, for the cost and value treatments, in uneven contests, the observed effort for both weak and strong groups are considerably higher under incomplete relative to complete information. In contrast, effort is about the same or is slightly lower for incomplete versus complete contests in the group size case.

Figure 1 plots average time-series by contest type, group type, and source of heterogeneity. In many cases, group-level effort decreases as the experiment progresses. This finding is consistent with prior experiments (e.g., Abbink et al. 2010, Fallucchi et al. 2021). With the possible exception of strong groups competing in an uneven contest with group size heterogeneity, the plots suggest

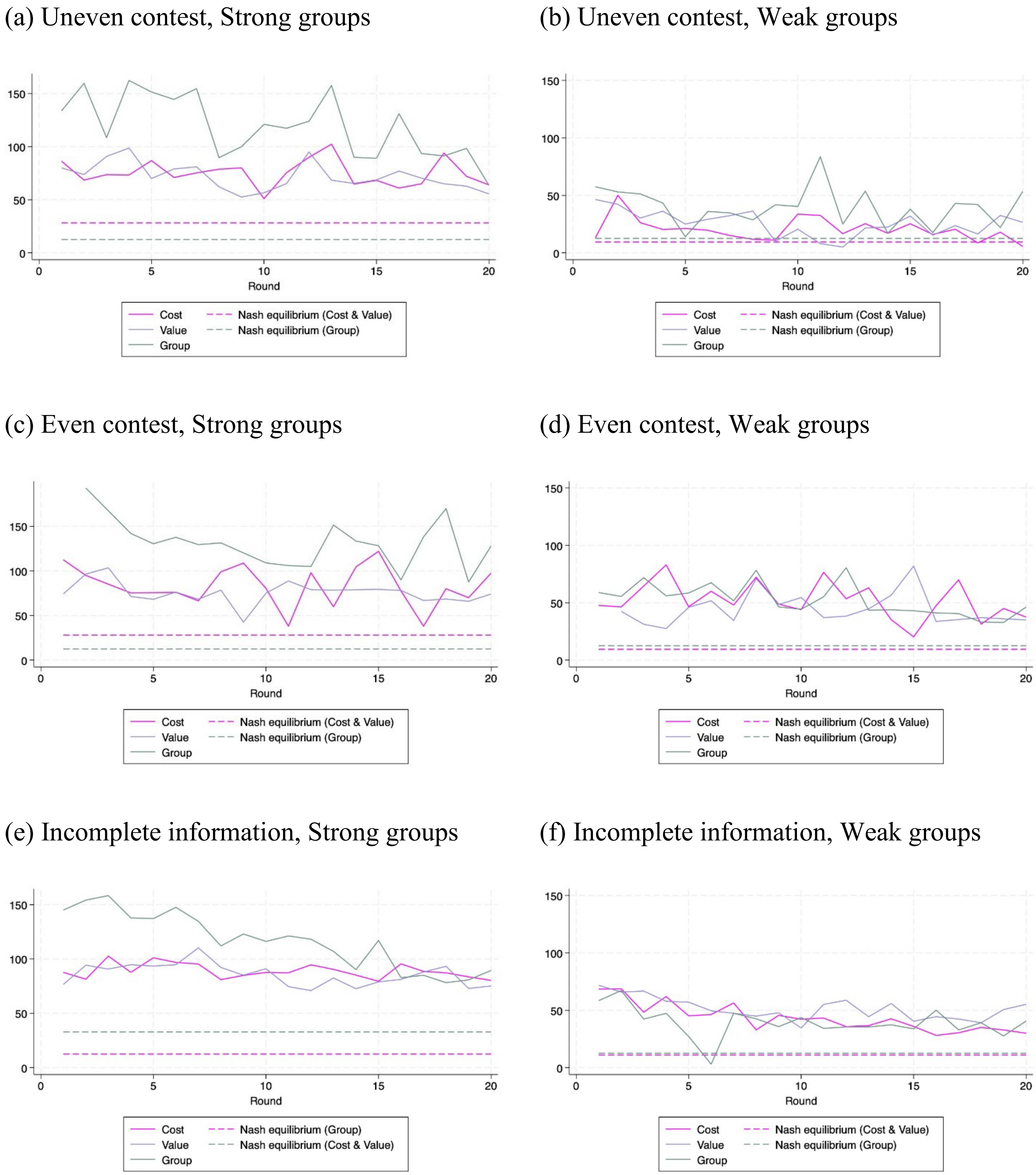

Figure 1. Time-series of group-level effort

that average effort has converged by the last round of the experiment.[15] Nevertheless, the presence of negative time trends, and what appear to be differences in trends across sources of heterogeneity, indicate that it is important to account for these dynamics in the subsequent regression analysis.

We use linear regressions of group-level effort to test our main hypotheses. It is however challenging to include covariates that account for participant characteristics in these regressions as this requires aggregating data across team members, which is especially problematic given variation in group size. We therefore include in the appendix parallel regression models using individual effort observations based on linear regressions (Table B.3 and B.4) and Tobit models (Table B.5 and B.6). These models demonstrate that controlling for participant characteristics has a negligible impact on treatment effect estimates - an expected finding given random treatment assignment.[16]

The strangers matching protocol should minimize correlations across groups either within a round or across rounds as most groups are unique. Nevertheless, as participants have a shared history, we allow observations within a decision round to be correlated, and further allow for observations in one round to be correlated with those in the previous round (a form of first-order serial correlation). This is accomplished through two-way, non-nested clustered standard errors.[17] In the regressions, we further use sampling weights to account for differences between the

[15] Our decision to run the experiment for 20 decision rounds was motivated by evidence from the pilot experiment, the results of which suggest that behavior converged well before the last round. It is an open question whether results would be robust to an increase in the number of decision periods.

[16] For the cost and value treatments, treatment effects based on individual and group effort logically differ by a factor of 3, and the two sets of models tell identical stories. For the group size treatments, differences between individual and group effort regressions are more nuanced. For example, if individuals exert similar or even slightly lower effort when in large versus small groups this translates to a much higher group-level effort for large groups. Therefore, care must be taken when interpreting the individual-level regression results in the context of our main hypotheses, which are based on group-level effort.

[17] One cluster variable defines clusters as successive pairs of rounds (i.e., 1&2, 3&4, …, 19&20), while the other defines similar clusters based on a one-period offset (1, 2&3, 4&5, …, 20). Together, this allows all observations in one round (e.g., round 3) to be correlated with both the prior round (round 2) and the next round (round 4). In defining clusters, observations from different sessions are assumed to be independent.

expected and actual frequencies a group (or an individual) was assigned to a specific contest type and group type.[18]

4.1. Effects of incomplete information

Table 6 presents regressions that allow for tests of the three Propositions.[19] Specification (1) allows for a direct test of incomplete information on effort, separately for each source of heterogeneity. Specification (2) further allows the effects of incomplete information to vary across the two complete information contest types (uneven and even). Specification (3) adds time trends. The time trend variable is demeaned so that estimated treatment effects can be interpreted as pertaining to the average round.

For cost and value treatments, specification (1) indicates that the effect of incomplete information is to increase effort by 10 to 14 points relative to the average complete information contest. This result rejects Hypothesis 1(c), which predicts a null effect. Specification (2) and (3) reveal that, consistent with Hypothesis 1(a), effort in an incomplete information contest is higher than for an uneven contest. However, theory predicts that incomplete information contests will result in lower effort than even contests. Coefficient estimates suggest the opposite effect, although differences between these two contest types are insignificant.[20]

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[18] Evident from the sample sizes reported in Table 7, the data include more even (54%) than uneven (46%) contests. Further, 52% of even contests are between weak teams, and 52% of teams in incomplete information contests are weak. Sampling weights are employed to adjust for these and other unanticipated differences due to unequal randomization. The sampling weights mirror those used for stratified random sampling. Here, a strata is defined by a unique combination of source-of-heterogeneity, contest type, and group type. The sampling weight for observations within a stratum is calculated as the expected number of observations divided by the actual number of observations. Observations in regressions are then weighted by (i.e., multiplied by) the inverse of the sampling weight.

[19] For regressions based on group-level observations, there are 720 observations each from the cost and value treatments, and 548 from the group size treatments.

[20] Based on specification (3), F-tests of equal group-level effort across even and incomplete information contests yield the following p-values: value (p=0.13); cost (p=0.95); group size (p=0.13).

For group size treatments, incomplete information has no statistical effect on group-level effort relative to either an even contest or an uneven contest. This evidence supports Hypothesis 2. Nevertheless, the very high effort levels in the group size treatments nevertheless cast doubt on the ability of standard theory to generally predict behavior.

Table 6. Analysis of group-level effort by contest type

Dependent variable: Group Effort			
	(1)	(2)	(3)
Value	-1.77	1.30	1.94
	(4.86)	(4.53)	(4.44)
Group	28.94***	32.79***	32.17***
	(5.85)	(5.27)	(4.86)
Cost × Incomplete	9.54**	18.31***	18.83***
	(4.75)	(4.22)	(3.96)
Value × Incomplete	13.69***	19.40***	19.24***
	(4.92)	(5.10)	(4.85)
Group × Incomplete	-5.91	-0.98	0.27
	(6.44)	(6.31)	(5.15)
Cost × Even		17.54***	18.48***
		(4.13)	(4.24)
Value × Even		11.41***	11.13***
		(3.57)	(3.54)
Group × Even		9.85	11.68*
		(6.89)	(6.66)
Cost × Decision Round			-1.15***
			(0.35)
Value × Decision Round			-0.76*
			(0.42)
Group × Decision Round			-1.93***
			(0.44)
Constant	56.34***	47.57***	47.11***
	(3.94)	(3.27)	(3.36)
Observations	1,988	1,988	1,988
R-squared	0.063	0.075	0.107

Notes: *** p<0.01, ** p<0.05, * p<0.1. Two-way clustered standard errors are in parentheses (see text for details). The regressions utilize sampling weights to adjust for unequal randomization into contest and group types. The covariate "Decision Round" is demeaned.

We summarize our main results below and emphasize through italics the findings that represent deviations from the standard theory model.

Result 1. For a contest where one team has a potential cost or value advantage, incomplete information increases effort relative to an uneven contest, has *no effect* on effort relative to the average even contest, and *increases* effort relative to the average complete information contest.

Result 2. For a contest where one team has a potential group size advantage, there are no differences in group-level effort between an incomplete information contest and an even contest, an uneven contest, or the average complete information contest.

4.2. Comparing sources of heterogeneity and group types

Regressions reported in Table 6 further allow effort comparisons across the cost, value, and group size treatments. From specification (1), in complete information contests, group-level effort is higher in group size treatments, by 29 to 31 points, relative to cost and value treatments. From (2) and (3), the higher efforts in group size treatments persist and are of similar magnitude across even and uneven contests. For incomplete information contests, the effort gap between group size and either value or cost treatments decreases to about 12 points, with differences being statistically significant.[21] These findings reject the theory prediction that increasing group size has no effect on group-level effort which, in turn, implies that we should see considerably lower effort for the group size treatments (Hypothesis 4).

[21] Based on specification (3), tests of equal group-level effort between group size and cost treatments yield the following: uneven ($p<0.01$); even ($p<0.01$); and incomplete ($p<0.01$). Tests of equal effort between group size and value treatments: uneven ($p<0.01$); even ($p<0.01$); and incomplete ($p=0.04$).

Result 3. For each contest type, group-level effort is *higher* in group size treatments relative to cost and value treatments.

Consistent with the theory, and in support of Hypothesis 3, effort is similar across the cost and value treatments. From (1), there is only a 1.8-point difference for complete information contests and a 2.4-point difference in the incomplete information case. Based on (2) and (3), the largest contest-level difference is 5.4 points (even contests, based on (3)). None of these differences are statistically significant.

Table 7 presents regressions that allow for effort differences between strong and weak groups, separately by contest type. It is clear from these regressions that there are very large differences in effort between strong and weak groups for the cost and value treatments, as anticipated [Hypothesis 5(a)]. These differences range from 31 points to 55 points. In contrast to the standard theory, which predicts a null effect, group-level effort is considerably higher for larger groups, and this effect ranges from 77 to 79 points. This evidence strongly rejects Hypothesis 5(b).

The regressions in Table 7 allow additional comparisons across potential sources of advantage. These regressions do reveal significant but modest differences in effort for weak groups across the cost and value treatments (for two of three contest types), but there are no significant differences across strong teams. Much of the difference between the group size treatments and the cost and value treatments stems from the relatively higher effort in strong teams. [22]

[22] Based on the regressions in Table 7, tests of effort differences for strong teams across cost and value treatments yield the following: uneven ($p=0.57$); even ($p=0.58$); incomplete information ($p=0.44$). For each contest type, group level effort is statistically different (and higher) for strong groups when comparing the group size treatment with either the cost or value treatment ($p<0.01$ in each case). For the uneven contest, group-level effort also differs when comparing group size treatment with cost or value for weak groups ($p<0.01$ in each case).

Table 7. Analysis of group-level effort across strong and weak groups, by contest type

Dependent variable: Group Effort			
	Uneven	Even	Incomplete info.
Value	7.37**	-6.06	8.34*
	(3.52)	(5.96)	(4.83)
Group	20.23***	1.19	-1.89
	(3.88)	(4.70)	(4.22)
Cost × Strong	54.94***	31.11***	45.66***
	(5.76)	(7.54)	(2.53)
Value × Strong	43.65***	32.76***	33.68***
	(2.79)	(3.93)	(3.84)
Group × Strong	78.43***	79.34***	76.78***
	(7.12)	(6.73)	(5.80)
Cost × Decision Round	-0.49	-0.84	-1.06***
	(0.50)	(0.63)	(0.33)
Value × Decision Round	-1.01*	-0.37	-0.85
	(0.51)	(0.57)	(0.64)
Group × Decision Round	-1.79***	-1.44**	-2.43***
	(0.58)	(0.62)	(0.41)
Constant	19.90***	49.91***	43.10***
	(2.19)	(4.50)	(2.26)
Observations	422	490	1,076
R-squared	0.585	0.466	0.499

Notes: *** p<0.01, ** p<0.05, * p<0.1. Two-way clustered standard errors are in parentheses (see text for details). The regressions utilize sampling weights to adjust for unequal randomization into contest and group types. The covariate "Decision Round" is demeaned.

Result 4. Based on a large set of comparisons, effort is similar across cost and value treatments.

Result 5. Group-level effort is higher for strong teams, regardless of the source of advantage or contest type.

Considering the trending effort levels evident from Figure 1, we estimated regressions that parallel the specifications in Table 6 and 7 but restrict the data to the last ten rounds (see Table B.7 and B.8). The main difference that arises is that, for incomplete information contests, effort is no longer statistically higher in the group size treatment relative to the cost and value treatments. Aside from this qualification to Result 3, the other main findings continue to hold.

We also estimated differences in the probability of winning between strong and weak teams, separately by source of heterogeneity and information condition, in cases where the actual contest was between a strong and a weak team (see Table B.9). Results suggest small but significant differences in winning probabilities across the cost, value, and group size treatments. Strong teams are roughly three times more likely to win. Overall, the analysis of the probability of winning conveys a narrative one would expect from the observed group-level effort differences.

4.3. Within-group heterogeneity

We next investigate heterogeneous behavior within groups using individual-level data. As in other social dilemma games, the possibility arises for players to free ride off the effort expenditures of other players. About 21% of individual-level effort expenditures (1506 of 7200 observations) are zero. Table 8 presents linear regression results for a dependent variable that equals 1 in cases where the participant contributed zero effort.[23, 24] Standard errors are clustered at the participant-level, in addition to the clustering assumed in the group-level regressions.[25] Players with prior participation in economics experiments and those classified as risk averse are more likely to free ride, whereas females are less likely to free ride. On average, free riding is 14 percentage points more likely in the last decision round of the experiment relative to the first round.

[23] Similar results arise if we use probit instead of linear regression (see Table B.10).
[24] Extending the model to allow for differences between cost and value treatments reveals no significant differences.
[25] There are negligible differences in standard errors and associated p-values if we instead calculate standard errors based only on participant-level clustering.

Table 8. Free-riding behavior and intra-group variation in individual effort

	Dependent Variable: Zero Effort	Dependent Variable: Contribution Variance
Group	-0.033	60.67**
	(0.050)	(25.74)
Incomplete	-0.172***	12.49
	(0.032)	(15.04)
Group × Incomplete	0.148**	-16.24
	(0.061)	(32.35)
Strong	-0.176***	28.14***
	(0.020)	(10.24)
Group × Strong	0.119***	-33.74*
	(0.034)	(18.41)
Even	-0.145***	14.07
	(0.021)	(13.12)
Group × Even	0.023	-57.66**
	(0.044)	(26.38)
Decision Round	0.007***	0.18
	(0.001)	(0.60)
Experience	0.073***	-34.08***
	(0.028)	(12.05)
Risk Averse	0.064**	-22.40**
	(0.028)	(11.27)
Female	-0.068***	6.76
	(0.025)	(11.32)
GPA	0.023	-13.56
	(0.033)	(12.27)
Constant	0.194*	184.07***
	(0.115)	(41.23)
Observations	7,200	7,200
R-squared	0.097	0.019

Notes: *** p<0.01, ** p<0.05, * p<0.1. Three-way clustered standard errors are in parentheses (see text for details). The regressions utilize sampling weights to adjust for unequal randomization into contest and group types.

For all treatments, players on a weak team in an even contest are about 15 percentage points less likely to free ride relative to those in an uneven contest. Further, there are no differences in free-riding behavior across treatments for the case of weak groups competing in an uneven contest.

Otherwise, differential patterns emerge between cost or value treatments when compared with group size treatments. For cost and value treatments, relative to being in an uneven contest, participating in an incomplete information contest decreases free riding by 17 percentage points. In contrast, the same effect for group size treatments is just 2.3 percentage points and is statistically insignificant (p=0.65). For cost and value treatments, being on a strong team reduces free riding by 18 percentage points. For the group size case, the effect is 5.7 percentage points (p=0.04).

We analyze as a second measure of within-group heterogeneity the squared deviation of a player's effort from the group mean, i.e., $(x_{ig} - \overline{x}_g)^2$. Given random re-sorting into groups, $\overline{x}_g$ is calculated separately for each group and decision round. In the extreme case where each group member makes the same effort choice, the measure equals zero. Analysis of this outcome variable is presented in the last column of Table 8. Some participant characteristics are strongly correlated with this variance measure. Within-group variation decreases with risk aversion, as well as participation in a prior economics experiment. The latter is suggestive of a learning effect. The contribution variance, however, does not vary as the experiment progress.

For the value and cost treatments, there is higher within-group variation among strong versus weak groups, but overall, within-group variation is similar across contest types. In contrast, for group size treatments, within-group variation is weakly lower in even relative to uneven contests (p=0.06) and there is no statistical difference across weak and strong teams (p=0.72). Overall, within-group variation tends to be higher among players on weak teams in group size treatments relative to cost and value treatments, and about the same across treatments for strong team members.

We also explored the extent to which the limited feedback provided at the end of each decision round shaped subsequent effort choices (see Table B.11). On average, a prior-round loss reduces effort in the next round by 1.9 points in even contests, 0.81 points in incomplete information contests, and has a statistically insignificant effect for uneven contests. The marginal effect of a one-point increase in group effort in the last round increases current round effort by 0.066, 0.079, and 0.076 points, respectively, for uneven, incomplete information, and even contests. The effects of either prior-round losses or prior-round group effort are not statistically different across contest types.

5. Consideration of behavioral motives

The literature hypothesizes the significance of behavioral motivations in group contests, as evidenced by effort levels far exceeding predictions of the self-interest model. Here, we consider the following possible motives: a non-monetary utility of winning, altruism towards one's group members, and hostility towards members of the competing group. In what follows we model these motives separately and focus on their implications for comparisons between complete and incomplete information contests.

Prior to conducting the experiment, we only considered the standard self-interest model presented previously and the in-group altruism model considered below. In response to feedback on a prior version of this paper, we were motivated to consider other behavioral motives. Had we considered all behavioral motives ex ante, this may have motivated additional treatments to better parse between them.

5.1. Non-monetary utility of winning

To allow the possibility that players have a 'joy of winning,' we extend the model so that the contest prize has both a monetary and a subjective, non-monetary component. Denote this "overall" prize value as $w(v_g)$, which is assumed to be (weakly) increasing in v_g, with $w(v_g) >$

v_g.[26] For notational convenience let $p_g(r)$ denote the probability of winning, conditional on the chance the opponent is a strong type, which is either 0 or 1 for the complete information case. The expected utility for a player can then be expressed as:

[9] $$U_{ig} = p_g(r)w(v_g) - c_g x_{ig}.$$

The equilibria for complete and incomplete information contests can be obtained by substituting $w(v_S)$ and $w(v_W)$ for v_S and v_W, respectively, in the formulas presented in Tables 1 and 2. It is straightforward to see that incorporating a non-monetary utility of winning increases predicted effort for both strong and weak teams, but does not alter the (directional) effects of incomplete information for any contest type. Propositions 1 to 3 continue to hold (see appendix).

5.2. In-group altruism

A natural extension is to assume that players derive utility based on the payoffs of other players within the group. Let $\alpha > 0$ denote the weight placed on these payoffs. The expected utility for a representative player is then (assuming players are symmetric):

[10] $$U_{ig} = p_g(r)v_g - c_g x_{ig} + \alpha \textstyle\sum_{j \neq i}\{p_g(r)v_g - c_g x_{jg}\}$$

$$= [1 + \alpha \cdot (n_g - 1)]p_g(r)v_g - c_g x_{ig} - \alpha \sum_{j \neq i} c_g x_{jg}$$

As for the case of a non-monetary utility of winning, in-group altruism serves to increase effort as now the marginal return from effort is higher. For the cost and prize value cases, regardless of information condition, altruism increases equilibrium effort by a factor of $1 + \alpha(n_g - 1)$. Propositions 1 and 3 continue to hold (see appendix).

[26] The utility of winning may be an increasing function of the group size, n. While we do not formally model this possibility, the in-group altruism model captures a similar phenomenon.

Of interest is that the model with in-group altruism predicts that group-level effort depends on group size, as utility is now a function of the gains and losses to other group members. Consequently, an increase in n_g increases the marginal utility from effort, and it follows that group-level effort is higher for a strong team. So, with the given form of altruism, group-level effort is strictly higher, and increases with group size.[27] However, the directional prediction for individual-level effort depends on the altruism parameter. Individual effort decreases, stays the same, or increases with group size depending on whether $\alpha < 1$, $\alpha = 1$, or $\alpha > 1$, respectively.

The predicted effects of incomplete information for the cost and prize value cases, as summarized by Proposition 1, now also hold for the group size case. In other words, Proposition 1 applies instead of Proposition 2 for this model. As evident from Table 1 and Table 2, for contests with possible cost or value heterogeneity, the ratio of strong and weak team effort is equal to the ratio of the cost (c_W/c_S) or value (v_S/v_W) parameters, respectively. With in-group altruism, the ratio of strong and weak team effort for the group size case is equal to $[1+\alpha(n_S-1)]/[1+\alpha(n_W-1)]$. When $\alpha = 1$, the effort ratio reduces to (n_S/n_W), which equals 3 in the experiment.

5.3. Out-group hostility

A player may derive disutility from the payoffs of competing group members. This could arise out of hostility towards the competitors or instead reflect preferences for relative payoff maximization. Let $\beta > 0$ denote a weight placed on the payoffs of the other group. Under complete information, the expected utility for a representative player is:

[11] $$U_{ig} = p_g(r)v_g - c_g x_{ig} - \beta\{(1-p_g(r))n_{-g}\, v_{-g} - c_{-g}X_{-g}\}.$$

[27] These results can be substantiated by comparing the equilibria for large (strong) and small (weak) groups presented in tables A.1 and A.2 in the appendix, and by comparing these equilibria to those from the self-interest model. In the appendix, for the special case of an uneven contest with group size heterogeneity, we show that group-level effort increases with group size.

The effect of out-group hostility varies in interesting ways depending on the source of advantage. Relevant for the cost heterogeneity case, the marginal effect of increasing effort is independent of the cost parameter for the other team. Equilibrium effort is scaled by βn relative to the standard self-interest model, and thus has an effect that parallels in-group altruism. For value contests, the marginal effect of effort is a function of the other team's prize value. Therefore, the effect of out-group hostility is enhanced in an uneven contest. As for the in-group altruism model, when motivated by out-group hostility, group size matters. Here, this effect arises because an increase in effort reduces the probability that the other team will win and, in turn, decreases the expected payoff by each member of the competing group. The overall effect of this decrease in the other team's win probability intensifies as the size of the other group increases.

Incomplete information introduces modelling complexity for the group size and value contests. To see this, the expected utility for a representative player is

$$[12] \quad U_{ig} = p_g(r)v_g - c_g x_{ig} - \beta\{r \cdot (1 - p_{g,S})n_S v_S + (1-r) \cdot (1 - p_{g,W})n_W v_W - rc_S X_S - (1-r)c_W X_W\},$$

and increasing effort alters the win probabilities, and in turn the expected payouts to the other team, conditional on the (latent) type of the other group. While strong teams continue to exert more effort than weak teams, the effects of incomplete information are ambiguous. When β and/or the extent of the advantage is relatively small, Proposition 1 continues to hold for prize value contests, and the same directional hypotheses as for the in-group altruism model for group size contests arise. The predictions are otherwise in the *opposite* direction. In the case of cost heterogeneity, the mathematics simplify, and equilibrium effort is scaled by βn relative to the standard model. Propositions 1 and 3 continue to hold for cost heterogeneity.

5.4. Reconciling theory and behavior

A robust finding from the experiment is that effort is similar across cost and prize value treatments. This contradicts the predictions of the out-group hostility model. Further, this result implies that, if a non-monetary utility of winning is important, this form of utility is proportional to prize value. In contrast, if non-monetary utility is additive, this would also lead to important differences between these two treatments. High effort levels in all treatments, including group size variations, indicate the importance of in-group altruism. Importantly, a model considering only non-monetary utility predicts that group-level effort does not depend on group size. Based on these observations, we fully developed the theory to incorporate both a non-monetary utility of winning, with $w(v_g) = v_g(1+\gamma)$, and in-group altruism.[28] With this specification, incomplete information increases effort relative to uneven contests, decreases effort relative to even contests, and has no effect on the average contest. Therefore, assuming this specific model ensures the theory results hold for all potential sources of advantage. Derivations and proofs are provided in the appendix.

To gain an understanding of the underlying structural parameters of the extended theory model, we considered estimating these parameters by selecting values that minimize the sum of squared deviations between the observed values presented in Table 4 and the theoretical predictions (i.e., the equilibria based on α and γ). An issue that arises is that, at least for the cost and value treatments, α and γ are perfectly linearly dependent and one cannot identify both parameters. As a compromise, we set $\gamma = 0$ and estimated α separately for each of the six cases defined by source of heterogeneity and information condition. These estimates vary from 0.66 to

[28] We assume that in-group altruism depends on both the monetary and non-monetary values of winning. Excluding the latter from the altruism term leads to theoretical differences across cost and prize value treatments.

1.29.[29] If we instead restrict α to be equal across treatments, the estimate is $\alpha = 0.99$. This matches well our prior of $\alpha = 1$ based on previous group contest experiments (see footnote 11).

Given the above result, included in column (2) of Table 4 are point predictions for the in-group altruism model with $\alpha = 1$. Note that in this special case, the prediction for all three sources of heterogeneity is that strong groups put forth three times more effort than weak groups.

The extended theory, assuming a sufficiently high altruism parameter, predicts the high effort levels observed in all contests. However, the empirical finding that effort is the same in even and incomplete information contests is not predicted by the extended theory model. We provide three possible explanations for this finding. First, people may hold subjective beliefs over the probability the opponent is a particular type, as suggested by Bhattacharya (2016). While we did not elicit beliefs over the opponent's type, it is plausible some players in incomplete information contests nevertheless formed beliefs that deviated from the objective probability. According to the theory, if players on a strong team believe the likelihood their opponent is also strong is greater than 50% ($r > 0.5$) this increases effort. One potential reason for biased beliefs is pessimism – that although you are on a strong team as (bad) luck would have it, the other team is also strong (Baharad and Nitzan 2008).

A second reason to increase effort is to minimize regret from losing (Hart et al. 2015). Such a motive should induce relatively higher effort for players in an incomplete information contest, as avoiding losing means they should behave as if their opponent is strong (even when there is only a 50% chance of this). We offer bounded rationality as a third possible explanation. Specification (4) in Table B.3 indicates that a higher GPA, a proxy for cognitive ability, has no statistically significant effect on individual effort in complete information contests. However, a

[29] We obtain the following estimates: cost-of-effort (complete) = 0.72; prize value (complete) = 0.66; group size (complete) = 1.29; cost-of-effort (incomplete) = 0.92; prize value (incomplete) = 0.90; group size (incomplete) = 1.26.

one-point increase in GPA decreases effort in incomplete information contests by about 5 points (p=0.01). Therefore, the estimated differences in effort between even and incomplete information contests, conditional on a high GPA, are better aligned with theory. It could be the case that low GPA individuals may be more likely to base decisions on subjective beliefs about their opponent's type, as speculated above.

6. Discussion

In this paper, we report on the first study that uses theory and experiments to compare behavior in inter-group contests where teams have incomplete information on the opponent's type (strong or weak) with complete information contests. We further consider three sources of heterogeneity across competing teams, specifically whether they potentially differ in terms of their cost-of-effort, the value of the prize received from winning the contest, or group size. These design variations provide a platform from which to evaluate a standard theory based only on self-interest to potential extensions that consider other behavioral motives.

Our main results challenge standard theory and provide support for a model of in-group altruism that assumes people derive utility from their own payoffs along with payoffs that accrue to other group members. Importantly, this model provides an explanation for the overbidding observed in all treatments and predicts that group effort increases with group size. The group size result from the experiment is dramatic. Relative to a baseline weak team, a strong team with a three-fold size advantage puts forth more collective effort than a strong team with either a three-fold advantage in terms of lower costs or higher prize values.

The findings generally lend support to our initial claim that uncertainty about the incentives facing the competing groups, such as the case of two law firms contending to secure a client, can alter effort and in turn inform contest design. For instance, and consistent with both theory and experimental results, if the client (the contest designer) is knowingly considering law firms with different talents (i.e., an uneven contest) and wishes to motivate a high collective effort (say, with the hope that initial discoveries will eventually lead to a favorable legal outcome), the client should do their best to induce an incomplete information contest by making sure that the law firms do not know who their competition is. In contrast, if effort in the contest is somewhat wasteful in the sense that it does little to promote the client's objectives, then instead the client should induce a complete information contest by making the identities of the competing firms known to one another. If the competing teams have similar talents (i.e., an even contest), then at least according to the experiment findings but in contrast to theory, whether the client discloses the identities of the competing firms does not matter.

Some of our results serve to extend prior findings to previously unexplored cases. In an uneven group contest with cost-of-effort heterogeneity, Bhattacharya (2016) finds that advantaged (strong) teams contribute significantly more effort than disadvantaged (weak) teams. This is consistent with our results, and we further demonstrate that this effect holds for different sources of advantage as well as under incomplete information. Further, prior studies (e.g., Abbink et al. 2010; Ahn, Isaac, and Salmon 2011) find that larger groups exert higher effort in a complete information setting, which is related to the group size paradox (Olson 1965). Prior group contest experiments use groups with five or fewer players and thus we demonstrate that the stylized fact continues to hold with nine-member groups, and under incomplete information.

It is natural to question whether the in-group altruism motive, especially given the size of the altruism parameter needed to reconcile theory and data, is the best explanation for observed behavior. Indeed, in the experiment players are rematched into different groups each decision round, and so why should someone “care” about their teammates, who may well have been opponents in a prior round? Regardless of the temporary nature of group affiliation in our experiment, it remains a consistent element of the collective endeavor to win the contest. This shared objective could foster a sense of temporary group identity, which may be sufficient to induce cooperative behaviors. Baik, Chowdhury and Ramalingam (2021) find that bids (i.e., efforts) in inter-group contests are invariant to whether partners or strangers matching protocols are used. One interpretation of this result is that group identity may be just as strong for a temporary group as it is for a more permanent group in this setting.

Moreover, Rusch (2014) discusses how parochial altruism theories are designed to elucidate cooperative behavior among non-related individuals, reinforcing the potential for temporary alliances to drive collective efforts. Therefore, our study contributes to this dialogue by suggesting that even fleeting alignments of interests within group contests can be sufficient to elicit cooperative behaviors, an effect that may be amplified in settings with stronger group identities.

Ultimately, we did not explicitly design the experiment to evaluate all the behavioral motives we consider, nor did we gather any corroborating empirical evidence that players were motivated by the welfare of their (transient) teammates. Future investigations could benefit from measures of cognitive ability, altruism, non-monetary utility of winning, subjective beliefs, and other potential behavioral drivers, determined through questionnaires, belief elicitations, or other experiments. While our conclusions are open to alternative interpretations, our study is the first in the group contest literature to use experiments to investigate alternative theories, and we hope our work encourages additional research on this topic.

Declaration of competing interest

We declare that we have not received financial support from any interested party, do not have any position in a relevant organization, and no other party had the right to review this paper prior to its circulation.

Data availability

The data and code for reproducing the empirical results are available through the Harvard Dataverse at https://doi.org/10.7910/DVN/5O0QVJ.

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