

Sequential Teamwork in Competitive Environments: Theory and Evidence from Swimming Data

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Abstract

We show that team members contributing earlier when team production is sequential have an incentive to free-ride more even when there is competition between teams. These predictions are tested on more than 300.000 observations on swimmers' performance at competitions from all over the world by comparing individual and relay swimming times. We find that free-riding does not vanish under competition and that earlier swimmers' performance in relays is relatively weaker.

Keywords: team production, contest, intergroup competition, sequential contribution, free-riding, swimming

JEL-Classification: C70, D20, D70, H40

1 Introduction

Team production is a fundamental characteristic of modern societies. Many activities require the joint effort of a multitude of participants and so teamwork has become prevalent in many firms. From 1987 to 1996 the share of firms having more than 20% of employees organized in teams rose from 37% to 66% (Lazear and Shaw, 2007). Generally, the reason why firms choose to form teams is that they are supposed to be more productive. The organization of teams in firms depends on the nature of tasks that have to be accomplished. Some tasks may require the simultaneous contribution of team members, other very common situations entail subsequent production phases that require sequential contributions by team members, where each contribution builds on previous work done by the other team members. Irrespective of the scope for which teams are used, it is well known that

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it can be time consuming to coordinate and organize them. Moreover, team production might be plagued by disincentive problems because individuals free-ride on the contributions of other team members (Alchian and Demsetz, 1972; Holmstrom, 1982), something the managers of teams and team members themselves constantly worry about. How to solve the free-riding problem becomes key, and letting teams compete may alleviate it. In a laboratory experiment Bornstein et al. (1990) compared the performance of groups in a social dilemma situation under two conditions: one in which groups were not facing competition and another in which groups were competing for an additional reward. They found that between-group competition significantly increased the contributions of the simultaneously acting team members, a finding that was replicated by Erev et al. (1993) in a different work environment where subjects picked oranges, as well as by Gunnthorsdottir and Rapoport (2006). Surprisingly, little seems to be known on whether competition between teams eliminates free-riding as team members contribute sequentially.

We want to progress in this direction with two contributions. We first develop a model where members of competing teams contribute sequentially to win a commonly shared price. Secondly, we provide an empirical assessment of free-riding within teams when there is competition between teams. Typically, it is difficult to measure the performance of workers in standard work situations, including the individual contributions to a common goal. This is why rewards are often shared among team members. Moreover, from a researcher's perspective it is usually infeasible to construct a convincing counterfactual that would allow to draw causal inference from the observations in an environment of an operating firm. In order to overcome these problems economists have increasingly turned to sports data recognizing that these markets provide a number of natural experiments for testing the effects of incentives and labour-market behavior (Szymanski, 2003). A well known attempt linking contest theory with data from sports is Ehrenberg and Bognanno (1990) who examined the size of prize funds on the scores of golfers at major tournaments. For testing our predictions we, too, turn to the sports area and draw on swimming data.¹ Our comprehensive dataset covers swimming competitions from all over the world during the years 1972 to 2009 with a total of more than 300,000 observations. It seems to be particularly suited for our purposes as it allows us to construct a counterfactual for each individual's performance by comparing times swam in individual races with the same swimmer's performance in a relay at the same event typically taking place within a time period smaller than 2 days. The evidence supports the prediction that competition between teams does not wash out the free-riding problem that typically arises with team production. Moreover, the data also confirms a prediction of our model that with sequential contribution team members moving earlier free-ride more.

Our contribution links to studies on incentive problems when contributions to

¹Existing studies employing swimming data mostly involve experimental work stemming from the area of social psychology with one of the earliest contributions by Sorrentino and Sheppard (1978), followed by Williams et al. (1989), Everett et al. (1992) or Miles and Greenberg (1993).

a public good are sequential. For example, in an experimental study Erev and Rapoport (1990) compared sequential and simultaneous contributions to public goods and showed that simultaneous choice is significantly less effective in solving the dilemma. Contrarily, Varian (1994) argued that with sequential choice the free-riding problem is exacerbated with respect to the simultaneous contributions mechanism, and that there exists a first mover advantage with early contributors contributing less. Experimental evidence specifically targeting Varian (1994) by Andreoni et al. (2002) confirms the first mover behavior but also states that the difference between simultaneous and sequential play vanishes to the end of the experiment, while more recent experiments by Gaechter et al. (2009) support the prediction that the overall contribution is lower in sequential contributions but do not find evidence for the predicted first mover advantage. None of this work, however, considers the effect of competition.

Technically, we extend the literature on between-group competition to sequential within-group contribution. For our theoretical model, we draw therefore on contest theory between groups, following Katz et al. (1990), Ursprung (1990), or Gradstein (1993) among others.² In section 2 we set-up the theoretical model. In section 3 we provide some background to the rules and main characteristics of swimming competitions, and in section 4 we present our data and empirical results. In section 5 we conclude.

2 A model of inter-group competition with sequential intra-group choices

We model competition between groups along the lines of contest theory which goes back to the seminal contribution by Tullock (1980). Tullock employed a contest success function (CSF) where the probability of winning the competition is equal to the ratio of own effort to global effort –the sum of efforts of all contenders.³ There are two teams A and B competing for a prize S . Each team has two players, denoted with 1 and 2. All players are of homogeneous ability. The prize S has equal value to each of the team members. Team members exert effort e at costs $c(e)$. We employ a quadratic cost function $c(e) = e^2$. As in Gunnthorsdottir and Rapoport (2006) the contributions of team members to the overall team output enter additively. To reflect the sequential nature of the game, however, first members of teams A and B choose their effort level first. Second players make their choice on the basis of first players' outcome. Thus, members 1 are Stackelberg leaders *vis à vis* members 2 in their teams. We denote with e_{A1} effort spent by the team member moving first in team A , and e_{A2} as effort spent by the team mem-

²Two recent surveys are Corchón (2007) and Konrad (2009).

³Tullock's idea was to compare rent seeking activity –group contribution in our setting– to the purchase of lottery tickets: the higher the number of tickets, the more likely to win the lottery. Skaperdas (1996) provided an axiomatic foundation for the Tullock CSF, while more recently Jia (2008) offered a distribution based justification for its ratio form.

ber who moves second in team A . Notation for team B is accordingly. The fact that effort is not deterministically transformed into performance, and that there are stochastic elements in the competition is taken into consideration by CSFs. In our setting, however, uncertainty is partly resolved after the first players finish their task. Hence, second players face a different informational content. We model this by introducing an additional random term ε with support $[0, 1]$. Realization of this random variable takes place before second players choose their effort, and is thus considered as given by second players, as is first players' effort.⁴ The winning probability of team A is then

$$p_A = \begin{cases} \alpha \frac{e_{A1} + e_{A2}}{e_{A1} + e_{A2} + e_{B1} + e_{B2}} + (1 - \alpha)\varepsilon & \text{if } e_{A1} + e_{A2} + e_{B1} + e_{B2} > 0 \\ \frac{1}{2} & \text{otherwise,} \end{cases} \quad (1)$$

with $0 < \alpha < 1$ being a relative weighting factor on the impact of the random component of first players' performance on the winning probability of the team. Accordingly, the probability of winning for the other team B is $p_B = 1 - p_A$. Expected payoffs for the second players are

$$V_{A2} = p_A S - e_{A2}^2 \quad (2)$$

$$V_{B2} = p_B S - e_{B2}^2 \quad (3)$$

where the realization of ε is known to them. Accordingly expected payoffs for first players who do not know the realization of ε at the time they make their choice are

$$V_{A1} = p_A S - e_{A1}^2 \quad (4)$$

$$V_{B1} = p_B S - e_{B1}^2. \quad (5)$$

The game is solved by backward induction. Second players take the effort level of first players as given, know the realization of ε , and choose their own effort simultaneously. Their effort choices follow from the first order conditions

$$H \equiv \frac{dV_{A2}}{de_{A2}} = \frac{e_{B1} + e_{B2}}{D^2} S - 2e_{A2} = 0 \quad (6)$$

$$F \equiv \frac{dV_{B2}}{de_{B2}} = \frac{e_{A1} + e_{A2}}{D^2} S - 2e_{B2} = 0 \quad (7)$$

with $D = e_{A1} + e_{A2} + e_{B1} + e_{B2}$. Expected marginal gains — equal to the sum of the marginal increase in the probability of winning as effort is increased times the valuation of the prize S — have to equal the marginal costs. Because of symmetry, we have $e_{A1}^* = e_{B1}^*$ and $e_{A2}^* = e_{B2}^*$. The solutions to the two quadratic equations above are, ruling out the negative effort choices,

$$e_{A2}^* = -\frac{e_{A1}}{2} + \sqrt{\frac{e_{A1}^2}{4} + \frac{S}{8}} \quad (8)$$

$$e_{B2}^* = -\frac{e_{B1}}{2} + \sqrt{\frac{e_{B1}^2}{4} + \frac{S}{8}}. \quad (9)$$

⁴This amounts to say that second players observe first players' performance.

As $\frac{d^2 V_{A2}}{d e_{A2}^2} < 0$ and $\frac{d^2 V_{B2}}{d e_{B2}^2} < 0$ these first order conditions constitute the best choice of the team members moving second. Equations (8) and (9) are the reactions function which the first players in the team are facing with respect to the effort choices of their teammates who follow. Both reaction functions are downward sloping implying that an increase of effort of the first player leads to a decrease in the teammate's effort who optimizes his behavior as he knows about the outcome of the player moving first. Thus effort choices within teams are substitutes, and it is this property which will essentially drive our result that second players exert more effort as we compare optimal choices within teams for first and second players.

Before we do so, however, we have to turn to the behavior of first players. These first players of teams A and B also decide on their effort simultaneously taking into account that their particular decision will have an impact on all subsequent swimmers, and not knowing the realization of ε . The first order conditions for these players after taking expectations over ε are⁵

$$\frac{d V_{A1}}{d e_{A1}} = \frac{(e_{B1} + e_{B2})(1 + \frac{d e_{A2}}{d e_{A1}} - \frac{d e_{B2}}{d e_{A1}})}{D^2} S - 2e_{A1} = 0 \quad (10)$$

$$\frac{d V_{B1}}{d e_{B1}} = \frac{(e_{A1} + e_{A2})(1 + \frac{d e_{B2}}{d e_{B1}} - \frac{d e_{A2}}{d e_{B1}})}{D^2} S - 2e_{B1} = 0 \quad (11)$$

using $e_{A1}^* + e_{A2}^* = e_{B1}^* + e_{B2}^*$ which is given in equilibrium because of symmetry. These two first order conditions determine the optimal effort choices of first players.⁶

Proposition 1 *In equilibrium, the effort level provided by first players is lower than the effort level provided by second players.*

Proof See Appendix A.

This result stems from the substitutability of within team members efforts. The team member moving first knows that an increase in his effort is leading to a decrease in the effort of the team member moving second. Thus higher effort on his side is not fully reflected in a larger chance of winning the competition but he would still have to burden the higher costs of effort.

So far we have highlighted that first players free-ride with respect to second players, *i.e.* they exert a lower effort. We now show that also the effort of second players is too low with respect to the one that would be optimal for the team as a whole.

Proposition 2 *In equilibrium, the effort level provided by second players is lower than the cooperative social optimum for the team.*

⁵We assume here that players are risk neutral. Should they be risk averse, our finding that first players exert less effort than second players would be reinforced, as they face more uncertainty.

⁶The second order conditions are satisfied as we show in the Appendix.

Proof See Appendix A.

Intuitively, the cooperative solution takes into consideration the fact that the prize S is non-rival and that effort exerted by any individual player has a positive externality on the team member. As marginal costs are increasing, it is advisable from a social point of view to share the burden equally among team members. Hence, $e_{A1}^* = e_{A2}^*$ (and $e_{B1}^* = e_{B2}^*$) for the cooperative solution.

Not only the second player exerts effort that is not socially optimal: it is also lower than the effort that the same individual would choose for an individual production. Moreover, the latter is the same as the cooperative social optimum for the team.

Proposition 3 *In equilibrium, the optimal level of effort for an individual production is the same as the cooperative socially optimal level of effort for a team production.*

Proof See Appendix A.

This result warrants an investigation into free-riding among first players in the empirical testing where we compare individual with relay swimming times as long as the valuation of the prize S by swimmers is equal for individual and relay competitions. In other words, it allows an additional test of the free-riding behavior, on top of what Proposition 1 suggests –namely that we should be able to detect that exerted effort of players increases towards the end of the competition, a result which is independent of potentially different valuation of prizes between relay and individual competitions.

3 Swimming competitions

Swimming competitions entail four competitive styles: freestyle, backstroke, breaststroke, and butterfly. Events are held in all of the competitive styles at varying distances (e.g. 100 meters, 200 meters, etc.) typically in 25 or 50 meter pools. In addition, there is a combination of the strokes swum by one swimmer called the individual medley. Rules for these swimming competitions, may they be national or international, are set by the Federation Internationale de Natation (FINA).⁷

Relays are a group of swimmers who either all swim the same style or each swim one different style in the order of backstroke, breaststroke, butterfly and freestyle (medley relay). Except for some specific (usually minor) events, relay teams according to FINA rules consist of four swimmers. Unless specified by the Promoter's conditions the nomination of team members and the relay swimming order must be made before the competition. Any relay team member may compete in a race only once. Teams may be changed between heats and finals provided they are from a pool of swimmers whose nomination was submitted for that event.

⁷These rules are accessible under www.fina.org.

World records are recognized for freestyle relays 4×100 and 4×200 meters, and the medley relay 4×100 meters for either sex in 25 meter and 50 meter courses.

Swimmers in individual competitions and the first swimmer in a relay competition start upon hearing the starting signal. In a relay all the following swimmers start after the previous swimmer touched the wall of the pool. Hence, individual and relay times are comparable only for first swimmers, as there is an advantage for all following swimmers in a relay in terms of reaction time: they can see their teammates coming closer and consequently fine tune their start. In fact, if a first swimmer in a relay competition swims a record time it gets approved which provides a strong argument for comparing, as we will do, the individual swimming time with the time swam as a first swimmer in a relay.

Time keeping is under the supervision of appointed officials. Various rules guarantee accurate measurement of swimmers' performances. Time keeping is either made by automatic equipment or manually. If manually registered there are three timekeepers and watches must be certified by the governing body. If two of three watches record the same time, the two identical times are the official time. If all three watches show different times the intermediate time is taken, and if only two of the three watches work the average time is calculated. In any case times are recorded to 1/100 of a second.

4 Empirical evidence

4.1 Data description

Our dataset was kindly provided by GeoLogix AG, a Suisse company which gets the data directly from the European Swimming Federation (LEN) and other participating federations. In total it comprises 311,784 observations of performances of individual swimmers at more than 7,000 events which took place worldwide between 1972 and 2009. The events included in our sample are both major events such as the Olympic Games, World Championships, European Championships, Pan Pacific Games, the Commonwealth Games or Universiades, and other events, like national championships. Only athletes who took part, in the same event and for the same style, both in the individual competition and in the relay are included.

As for the *personal characteristics* of the swimmers, we have information on age, gender, nationality, club membership, and FINA points. Age is between 6 and 109 years with a median of 16. Gender composition of the sample is more or less equally split. FINA points allow comparisons of results among different events. The FINA Point Scoring assigns point values to swimming performances, more points for world class performances –typically 1000 or more– and fewer points for slower performances. Points are assigned at every competition, by comparing a swimmer's performance with a base time that is recalculated every year, based on the average of the top ten of the All Time World Rankings.⁸ In the sample FINA

⁸For example, in the year of the Olympic Games in Beijing Michael Phelps had 1,063 FINA

points are related to the individual competitions and vary between 5 and 1,181 with a median of 504. Next we have information on the *event* (event name, location and beginning and ending day), the *competition* (style, distance, date of attendance and round – heats, preliminary, semifinals, or finals) with the day of the competition allowing to some extent to control for the sequence of the individual and the relay race, and finally *performances*, which include the time in the individual and the relay competition, the total relay time, as well as the starting order in the relay and the final placement both for the relay and the individual competition. Table 1 summarizes the data.

4.2 Descriptive evidence

Table 2 reports the relative difference in swimming time between the relay and the individual competition for different starting orders in the relay. As we have already noted, direct comparison between the relay and the individual competition is possible only for first swimmers, as subsequent swimmers enjoy an advantage in terms of reaction time, given that they can see the previous swimmer approaching the end of his/her leg. The table clearly shows that first swimmers are, on average, slower in relays, with respect to their performance in the individual competition. In the whole sample (66,561 observations, with an average swimming time in the individual competition of 56.84 seconds), this difference amounts to .22%, that is 12/100 of a seconds in absolute terms.

Testing the relative difference against the null of there being no difference in performance yields a highly significant p-value. This result is robust against splitting the sample along gender or age. It is furthermore valid for swimmers with higher or lower FINA points than the median swimmer. It also holds over all styles if we focus on the sign of the difference in swimming times and in 6 out of 7 subgroups for the various styles in terms of significance.

One might be concerned that training or the use of illegal substances targeted to a specific competition (individual or relay) might disturb our results. However, there is no reason to believe that something like this is driving the results. Individual and relay competitions are generally very close to each other: they are within 1 day of separation in 87% of the observations implying that training efforts influence individual and relay competitions equally. With illegal substances targeting longer term goals such as the building up of red blood cells basically the same logic applies as with legal training methods. One might also be concerned that fatigue decreases performance in later events: however, the distribution of days of separation between individual and relay competitions is quite symmetric. In any case, we also split the sample along the timing of competitions to check whether it makes a difference if the individual race took place before or after the relay at the particular swimming event for which we compare the swimming times. It is still true that relay performances are weaker than individual performances. Finally

points for the 200m freestyle competition.

our result is also valid if we look into major events only. Overall, if one is willing to accept the hypothesis of equally valuable prizes in the individual and the relay competition, this evidence is consistent with the implications of Propositions 2 and 3 of our theoretical model, suggesting the presence of free-riding in relays.

Table 2 also reports the relative difference for subsequent swimmers. Here, the first thing to note is that swimmers starting 2nd to 4th in the relay are on average faster than in individual competition, coherently with the existence of a reaction time advantage. Moreover, last swimmers in relays seem to be faster than swimmers starting 2nd or 3rd, and there seems to be a small difference, in the broad averages, between swimmers starting 3rd and swimmers starting 2nd. In order to further elaborate on these differences we turn to a multivariate analysis which allows us to fully exploit our dataset.

4.3 Regression analysis

The dependent variable that we use in the multivariate analysis is the relative difference between relay and individual swimming times, as already introduced in table 2. In order to control for the reaction time and to test for our theoretical prediction we introduce dummy variables for the starting order in the relay competition. Other controls are gender, age⁹, style, type of the competition (major vs. non-major) and schedule (whether the individual competition is on a day before the relay, on the same day, or on a day after). Because of reaction time issues there is an advantage in terms of achievable swimming times for all swimmers that start after the first one. We thus expect the coefficient of the dummy variable for the first swimmer in the relay to be positive (first swimmers in the relay are slower than in the individual competition), but the coefficients for the dummy variables for subsequent swimmers to be negative. As our theory of sequential contribution to team production under competition proposed that later swimmers should on average exert more effort we would expect that the order dummies change in size with higher orders becoming more negative.

This is what we find (as shown in table 3, Model 1): the estimated parameter for the dummy for the first swimmer in the relay is .08% (the constant); second, third and fourth swimmers entail a reduction in the relative time gap of .66%, .68% and .95%, with respect to first swimmers. All dummies are highly significant with p-values smaller than .001. The Wald tests reject equality of the coefficients of the order two, three and four dummies at a high level of significance. As for the other controls, we find that female swimmers and young and old age groups perform relatively worse in relays, while the gap in relative performance is reduced in major events.

Should one be concerned that certain swimmers are always allocated to certain

⁹We use three age groups rather than a continuous age variable, in order for the coefficients of the starting order dummy variables to show the effects of the starting order for the reference group (swimmers aged 15-30), rather than for swimmers of a specific age; the consequential reduction in explanatory power –as measured by R^2 – is very small.

order slots in a relay because of their characteristics? If this was the case one might be inclined to argue that the regression picks up team composition issues such as a team manager knowing which swimmer is particularly valuable at which order of the relay rather than the free-riding problem fading out to the end of the relay as we argue. For instance, should team managers put more motivated athletes as the last swimmers in the relay, we would have less motivated first swimmers, something that could explain their slower performance.

To control for (time invariant) unobservable characteristics of our swimmers we introduce individual fixed effects (Model 2). By doing so, we compare the difference one specific athlete scored between relay and individual time when swimming second, third or fourth in the relay, with the difference the same athlete scored when swimming first in the relay (in different events). This limits the number of observations to 107,808 as all records pertaining to swimmers for which there is no variation in the independent variables have to be dropped, but avoids composition bias. The coefficient for the `order_1` dummy (the constant) is now .51.¹⁰ The coefficients for the other order dummies are now -.71, -.78 and -1.03, respectively. Hence, the fixed effect model confirms our previous findings (and our theoretical model), and suggests that first swimmers are generally of (unobserved) good quality –a strategy that is often reported by trainers.

4.4 Robustness analysis

One could object that free-riding depends on the competitive pressure, and that our results are driven by competitions that are either not so close, or of minor importance. Our findings that the relative performances in relays are worse for swimmers at the beginning and at the end of their career, and improve in major events (Model 1) confirm this intuition. As a robustness check, we thus estimate our fixed effect model on finals only, both for the relay and the individual competition (Model 3), on the assumption that finals are more competitive. This restricts the sample to 25,138 observations. All our results are confirmed: the coefficient for the first order dummy (the constant) is still positive (.81), while the coefficients for the second, third and fourth order dummy variables are negative, decreasing and significantly different from each other: -.75, -.83, -1.23 respectively.

4.5 Size of the effects

While the results are supporting our theoretical propositions, one may wonder if these effects are of any meaningful size. In order to get a better understanding of the size of the effects that we detected, we look into the time differences by final placements, i.e. the average lag in swimming time between individuals belonging

¹⁰This value cannot be fully compared with the corresponding value of Model 1, as the age group variable is not included (in a fixed effect model, it would be estimated only on ages around the age group thresholds). Running Model 1 without controlling for age group entails a coefficient for the `order_1` dummy (the constant) equal to .18.

to teams that finished in n th place in relays and individuals belonging to teams that finished in $n - 1$ th place, for $n > 1$. This lag is, on average among the first 10 positions in the final ranking, .23% for major events and 1.35% for non-major events. These figures can be compared to the ones in table 2: for first swimmers at a major event we calculated a relative time difference between relay and individual competition of 0.03%, whereas the relative time difference for all other events amounts to 0.22%.

If we turn to the regression results (table 3, Model 2) we get an impact that is even more relevant: athletes in our reference category are on average .51% slower in relays than in individual competitions compared to an average lag over an immediately preceding team of .78% for this group (100m male freestyle, non-major events, swimmer aged 15-30).

Assessing the relevance of the finding that effort decreases as team members get involved in earlier stages of the production process, involves looking at the difference between the coefficients of second, third and fourth order dummies in table 3. Comparing the estimated effect of the fourth swimmers with the third swimmers yields a reduction in free-riding of $1.03 - .78 = .25\%$, relative to the relay swimming time. This value must again be compared with an average lag over the preceding team of .78%, and accounts for one third of this lag. The detected effect between third and second swimmers is smaller ($.78 - .71 = .07\%$), but still sizeable. By comparing the value of the fourth order dummy with that of the second order dummy we get a reduction in free-riding of .32% of swimming time, which should be regarded as a lower bound in the overall reduction of free-riding (since it is not possible to assess the reduction between first and second swimmers, due to the presence of a reaction time advantage for first swimmers).

5 Conclusions

In this paper we developed a simple model of sequential contributions to a team when teams compete against each other. We showed that in such a setting there is free-riding among team members even under competition between teams as the prize for winning a competition is non-rival and effort exerted by any individual player has a positive externality on the team members. We also showed that team members contributing earlier to a team's common task contribute less than the team members contributing later. The mechanism underlying the result is substitutability of inputs between team members to a Tullock contest. At the margin a team member contributing earlier refrains to increase costly efforts as he can foresee that the following team members will reduce their input so that on aggregate a team's effort for winning the competition would not change. In a cooperative solution and from a social point of view it would be optimal to share the burden equally among team members. But this does not happen even under between team competition as individuals contribute sequentially to the team.

Drawing on a unique data set of more than 300,000 observation from swim-

ming competitions from all over the world during the last four decades we find evidence for free-riding and the pattern of efforts over the course of sequential contributions to a team as suggested by our simple model. The basic idea which we employed was to compare for a given event the swimming performance of individual swimmers for single and relay competitions. By definition no free-riding occurs in a single competition which is why swimmers should exert full effort at these occasions. Taking their performance for the individual race as a control we found that on average these swimmers swam slower in relays. Moreover, controlling for reaction times and individual effects we found that free-riding diminishes as we move from the second, to the third and finally the fourth swimmer in the relays. Results are also robust against including various controls. Furthermore, the estimated time differences occur to be of meaningful size if compared to average time differences of swimmers winning a competition as opposed to being second, third, or fourth.

Our attribution of the lower performances in relay with respect to individual competitions to free-riding depends on the assumption that the prize S is equally valuable in relays and individual competitions. This assumption might be questioned: even with equal monetary prize, obtaining it in an individual competition might be more valuable as the honors do not have to be shared.¹¹ If this was the case, it could be socially optimal to individually provide less effort in relays, and our empirical analysis of Propositions 2 and 3 would not allow us to detect any inefficiency. We do not counteract to this remark (although it could be argued that for a vast majority of athletes what matters in winning a gold medal in their career is that they are gold medalist, and differences in utility from winning it in the individual competition rather than in the relay are, if any, of minor importance). What is more important, however, is that our result that there is free-riding *within* team, and that this free-riding is stronger for early contributors, remains unaffected from a potentially different valuation of prizes won in relays and individual competitions. Given that team production is often unavoidable, and that, as we have shown, competition does not solve the free-riding problem, this result points to the necessity of devising better monitoring or incentive mechanisms.

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¹¹The other side of 'two in distress make sorrow less'.

Appendix A

Proposition 1

Proof The proof is in two parts: we first show that the f.o.c. define the optimal effort level for players 1 as the s.o.c. are also satisfied; then, we show that the optimal effort level for players 1 is lower than the optimal effort level for players 2.

Expected payoffs for the first player of team A (analogously for team B) are:

$$V_{A1} = p_A S - e_{A1}^2 \quad (12)$$

with the f.o.c. as shown in the main text being

$$\frac{dV_{A1}}{de_{A1}} = \frac{(e_{B1} + e_{B2})(1 + \frac{de_{A2}}{de_{A1}} - \frac{de_{B2}}{de_{A1}})}{D^2} S - 2e_{A1} = 0. \quad (13)$$

The solution to this equation is the optimal choice of effort for player 1, given that the s.o.c. is satisfied. To see that this is indeed the case, consider

$$\begin{aligned} \frac{d^2 V_{A1}}{de_{A1}^2} &= \frac{D^2(\frac{de_{B2}}{de_{A1}}(1 + \frac{de_{A2}}{de_{A1}}) + (e_{B1} + e_{B2})\frac{d^2 e_{A2}}{de_{A1}^2})}{D^4} S \\ &\quad - \frac{D^2((1 + \frac{de_{A2}}{de_{A1}})\frac{de_{B2}}{de_{A1}} + (e_{A1} + e_{A2})\frac{d^2 e_{B2}}{de_{A1}^2})}{D^4} S \\ &\quad - \frac{((e_{B1} + e_{B2})(1 + \frac{de_{A2}}{de_{A1}}) + (e_{A1} + e_{A2})\frac{de_{B2}}{de_{A1}})2D(1 + \frac{de_{A2}}{de_{A1}} + \frac{de_{B2}}{de_{A1}})}{D^4} S - 2 \end{aligned} \quad (14)$$

We can find expressions for $\frac{d^2 e_{A2}}{de_{A1}^2}$, $\frac{d^2 e_{B2}}{de_{A1}^2}$ and $\frac{de_{A2}}{de_{A1}}$ by taking the total derivatives around the optimal solution for second players given by the f.o.c.:

$$\frac{\partial H}{\partial e_{A2}} \frac{de_{A2}}{de_{A1}} + \frac{\partial H}{\partial e_{B2}} \frac{de_{B2}}{de_{A1}} + \frac{\partial H}{\partial e_{A1}} = 0 \quad (15)$$

$$\frac{\partial F}{\partial e_{A2}} \frac{de_{A2}}{de_{A1}} + \frac{\partial F}{\partial e_{B2}} \frac{de_{B2}}{de_{A1}} + \frac{\partial F}{\partial e_{A1}} = 0. \quad (16)$$

Rewriting in matrix form yields

$$\begin{pmatrix} \frac{\partial H}{\partial e_{A2}} & \frac{\partial H}{\partial e_{B2}} \\ \frac{\partial F}{\partial e_{A2}} & \frac{\partial F}{\partial e_{B2}} \end{pmatrix} \begin{pmatrix} \frac{de_{A2}}{de_{A1}} \\ \frac{de_{B2}}{de_{A1}} \end{pmatrix} = \begin{pmatrix} -\frac{\partial H}{\partial e_{A1}} \\ -\frac{\partial F}{\partial e_{A1}} \end{pmatrix}. \quad (17)$$

Applying Cramer's rule we get for the effect of a change in the effort of the agent moving first in team A on the optimally chosen effort of the second team member in A

$$\frac{de_{A2}}{de_{A1}} = \frac{-uv + xw}{yv - zx} \quad (18)$$

and for the effect on the optimal effort of the second player in team B

$$\frac{d e_{B2}}{d e_{A1}} = \frac{-yw + zu}{yv - zx}. \quad (19)$$

Furthermore we have

$$\frac{d^2 e_{A2}}{d e_{A1}^2} = \frac{u'(u - v)}{v^2} \quad (20)$$

$$\frac{d^2 e_{B2}}{d e_{A1}^2} = \frac{v'(v - u)}{v^2} \quad (21)$$

with

$$u \equiv \frac{\partial H}{\partial e_{A1}} = \frac{-(e_{B1} + e_{B2})2D}{D^4} S < 0 \quad (22)$$

$$v \equiv \frac{\partial F}{\partial e_{B2}} = \frac{-(e_{A1} + e_{A2})2D}{D^4} S - 2 < 0 \quad (23)$$

$$w \equiv \frac{\partial F}{\partial e_{A1}} = \frac{D^2 - (e_{A1} + e_{A2})2D}{D^4} S = \frac{1 - \frac{2(e_{A1} + e_{A2})}{D}}{D^2} S = 0 \quad (24)$$

$$x \equiv \frac{\partial H}{\partial e_{B2}} = \frac{D^2 - (e_{B1} + e_{B2})2D}{D^4} S = \frac{1 - \frac{2(e_{B1} + e_{B2})}{D}}{D^2} S = 0 \quad (25)$$

$$y \equiv \frac{\partial H}{\partial e_{A2}} = \frac{-(e_{B1} + e_{B2})2D}{D^4} S - 2 < 0 \quad (26)$$

$$z \equiv \frac{\partial F}{\partial e_{A2}} = \frac{D^2 - (e_{A1} + e_{A2})2D}{D^4} S = \frac{1 - \frac{2(e_{A1} + e_{A2})}{D}}{D^2} S = 0 \quad (27)$$

$$u' \equiv \frac{\partial^2 H}{\partial e_{A1}^2} = \frac{3S}{D^3} > 0 \quad (28)$$

$$v' \equiv \frac{\partial^2 F}{\partial e_{A1} \partial e_{B2}} = \frac{S}{D^3} > 0 \quad (29)$$

$$w' \equiv \frac{\partial^2 F}{\partial e_{A1}^2} = -\frac{S}{D^3} < 0 \quad (30)$$

$$x' \equiv \frac{\partial^2 F}{\partial e_{A1} \partial e_{B1}} = \frac{S}{D^3} > 0 \quad (31)$$

$$y' \equiv \frac{\partial^2 H}{\partial e_{A1} \partial e_{A2}} = \frac{3S}{D^3} > 0 \quad (32)$$

$$z' \equiv \frac{\partial^2 F}{\partial e_{A1} \partial e_{A2}} = -\frac{S}{D^3} \quad (33)$$

Note that $u' = y'$, $v' = x' = -w' = -z'$. Because of symmetry we have $e_{B1} + e_{B2} = e_{A1} + e_{A2}$ so that in equilibrium $\frac{d e_{B2}}{d e_{A1}} = 0$. Hence the s.o.c. simplifies

to

$$\frac{d^2 V_{A1}}{d e_{A1}^2} = (e_{B1} + e_{B2}) \frac{D(\frac{d^2 e_{A2}}{d e_{A1}^2} - \frac{d^2 e_{B2}}{d e_{A1}^2}) - 2(1 + \frac{d e_{A2}}{d e_{A1}})^2}{D^3} S - 2. \quad (34)$$

Inserting $\frac{d^2 e_{A2}}{d e_{A1}^2}$, $\frac{d^2 e_{B2}}{d e_{A1}^2}$ and $\frac{d e_{A2}}{d e_{A1}}$ in equation (34) and further rearranging yields

$$\frac{d^2 V_{A1}}{d e_{A1}^2} = \frac{2S}{D^2} \left(\frac{S}{D^2} - 6 \right) - 8 \quad (35)$$

which is negative if

$$\frac{S}{(2e_{A1} + 2e_{A2})^2} < 6. \quad (36)$$

Using equation (8) one can show that the l.h.s. is never larger than 2 which finally proves that the s.o.c. is fulfilled.

Now, in order to have an interior solution and to show that the second player exerts more effort it must hold that:

$$-1 < \frac{d e_{A2}}{d e_{A1}} - \frac{d e_{B2}}{d e_{A1}} < 0 \quad (37)$$

which follows from the comparison of the f.o.c. of the first and second players. We already know that $\frac{d e_{B2}}{d e_{A1}} = 0$ and $\frac{d e_{A2}}{d e_{A1}} = -\frac{u}{y} = -\frac{u}{v}$. As $|u| < |v|$ it holds that $-1 < \frac{d e_{A2}}{d e_{A1}} - \frac{d e_{B2}}{d e_{A1}} < 0$ which proves our Proposition.

Proposition 2

Proof Due to symmetry, the choices of competing swimmers of the same order must be identical. From the f.o.c. of second players given in (6) and (7), by substituting $e_{B1} = e_{A1}$ and $e_{B2} = e_{A2}$, we find that the optimal effort level of second swimmers is implicitly given by:

$$c'(e_{A2}) = 2e_{A2} = \frac{S}{4(e_{A1} + e_{A2})} \quad (38)$$

or, equivalently, by $c'(e_{B2}) = 2e_{B2} = \frac{S}{4(e_{B1} + e_{B2})}$.

From a cooperative perspective, given that the prize is non-rival within the team, the optimal level of effort maximizes:

$$V_A = 2p_A S - e_{A1}^2 - e_{A2}^2. \quad (39)$$

The f.o.c. with respect to the effort choices e_{A1} and e_{A2} for team A (analogously for team B) are:

$$\frac{2(e_{B1} + e_{B2})}{D^2} S - 2e_{A2} = 0 \quad (40)$$

$$\frac{2(e_{B1} + e_{B2})}{D^2} S - 2e_{A1} = 0. \quad (41)$$

Symmetry then implies

$$2e_{A1} = 2e_{A2} = \frac{S}{2(e_{A1} + e_{A2})} = \frac{S}{4e_{A2}} \quad (42)$$

which is higher than the effort exerted by the second player in the non-cooperative solution given by 38.

Proposition 3

Proof From equation (38), absent player 1, player 2's optimal effort would be determined by:

$$c'(e_{A2}) = 2e_{A2} = \frac{S}{4e_{A2}} \quad (43)$$

which is the same as the socially optimal effort in team production.

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Table 1: Descriptive statistics

Variable			
Number of events		7,081	
Overall no. of observations		311,784	
(of which:)			
Olympic games		660	
World championships		1,531	
European championships		766	
Pan Pacific games		390	
Commonwealth games		184	
Universiades		304	
Style			
50m Breaststroke		20,092	
50m Fly		17,619	
50m Freestyle		103,086	
100m Breaststroke		28,719	
100m Fly		25,184	
100m Freestyle		96,034	
200m Freestyle		21,050	
Schedule			
individual first ^(a)		80,825	
relay first ^(b)		83,292	
same day		147,667	
Round (individual competition)			
timed finals (default)		144,436	
finals		75,862	
semi-finals		2,630	
preliminars		88,596	
others ^(c)		260	
Round (relay)			
timed finals (default)		202,384	
finals		94,807	
preliminars		14,025	
others ^(c)		568	
Order (relay)			
1st		66,551	
2nd		88,593	
3rd		80,004	
4th		76,636	
Gender			
male		155,341	
female		156,443	
	Median	Min	Max
Age	16	6	109
FINA points	504	5	1,181

(a) Day of individual competition before day of relay +

(b) Day of individual competition after day of relay

(c) Swim-Off after semi-finals, Swim-Off after preliminars

Table 2: Comparing individual and relay swimming times only

	Individual (secs.) I	Swimming times				
		Relative difference b/w relay and individual (%)				
		$\frac{R_1-I}{I}$	$\frac{R_2-I}{I}$	$\frac{R_3-I}{I}$	$\frac{R_4-I}{I}$	
Overall	56.84	.22 ***	-.33	-.34		-.75
Gender						
male	53.66	.20 ***	-.43	-.42		-.82
female	58.01	.23 ***	-.25	-.26		-.69
Age (yrs)						
< 15	54.91	.36 ***	-.03	-.02		-.47
15 – 30	58.47	.11 ***	-.48	-.51		-.92
> 30	38.78	.30 ***	-.58	-.51		-.95
Ability of swimmer ^(a)						
≤ median	52.64	.27 ***	-.19	-.17		-.59
> median	59.03	.17 ***	-.48	-.53		-.92
Style						
50m Breaststroke	39.67	.44 ***	-.51	-.12		-.25
50m Fly	33.58	.62 ***	-.10	-.48		-.32
50m Freestyle	32.03	.32 ***	-.70	-.70		-1.14
100m Breaststroke	78.27	.32 ***	-.05	-.05		-.22
100m Fly	67.88	.05	-.53	-.04		-.47
100m Freestyle	63.08	.14 ***	-.30	-.31		-.45
200m Freestyle	128.53	.07 ***	-.03	-.08		-.04
Event importance						
major events ^(b)	70.99	.03	-.53	-.56		-.90
others	55.66	.22 ***	-.33	-.34		-.75
Schedule of competitions						
individual first ^(c)	54.81	.19 ***	-.39	-.41		-.98
relay first ^(d)	59.81	.15 ***	-.49	-.49		-.77
same day	54.17	.27 ***	-.22	-.21		-.63

I - individual competition swimming time

R_1, \dots, R_4 - relay swimming time, starting order 1, \dots , 4

(a) As measured by FINA points

(b) Olympic, Pan Pacific and Commonwealth Games, World and European Championships, Universiades

(c) Day of individual competition before day of relay

(d) Day of individual competition after day of relay

*** $p < .01$

Table 3: Regression results

Dependent variable	Model 1		Model 2		Model 3	
	$(R - I)/I$					
constant	.08	***	.51	***	.81	***
order_2	-.66	***	-.71	***	-.75	***
order_3	-.68	***	-.78	***	-.83	***
order_4	-.95	***	-1.03	***	-1.23	***
female	.07	***				
age <15	.52	***				
age >30	.26	***				
major	-.19	***	-.14	***	-.31	***
same day	.19	***	.10	***	.02	
relay first	-.02	**	-.04	***	.02	
50m Breastroke (5)	-.27	***	-.46	***	-.61	***
50m Fly (6)	-.22	***	-.37	***	-.42	***
50m Freestyle (7)	-.48	***	-.72	***	-.61	***
100m Breastroke (1)	.27	***	.32	***	.27	***
100m Fly (2)	.33	***	.39	***	.41	***
200m Freestyle (4)	.21	***	.31	***	.25	***
Fixed effects	No		Yes		Yes	
R-squared	0.09		.50		.56	
Wald test (F value)						
order_2=order_3	3.93	**	30.88	***	5.67	**
order_3=order_4	822.12	***	522.59	***	155.93	***
Obs.	311,784		107,808		25,138	
Notes					finals only	

*** $p < .01$, ** $p < .05$

Reference category: 100m Freestyle, age group 15-30, individual competition on a day prior to the relay, first swimmers