

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

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Abstract

We develop a model of free-riding in teams when team production is sequential and there is competition between teams. Our predictions that free-riding does not vanish under competition and that team members contributing earlier have an incentive to free-ride more are tested on more than 300,000 observations on swimmers' performance at competitions from all over the world. We find that swimmers in relays perform weaker as compared to their individual performance, and that earlier swimmers' performance in relays is weaker relative to later swimmers.

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

JEL-Classification: C70, D20, D70, H40

1 Introduction

In this contribution we look into team production when team members sequentially contribute to the team, and teams compete against each other.

Team production is a fundamental characteristic of modern societies. Many activities require the joint effort of a multitude of participants and so teamwork

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has become prevalent in many firms. For instance, from 1987 to 1996 the share of US firms having more than 20% of employees organized in teams rose from 37% to 66% (Lawler et al., 2001; Lazear and Shaw, 2007).

The specific 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.

Drafting of documents is one example. A bad draft requires more effort by the people working on it at later stages in order to achieve a certain level of quality. Another example relates to the training of students at universities. Colleagues who do a proper job teaching first year courses select and prepare students well for courses to be taught by other faculty in the second year. Finally, one may think of mail delivery. In many countries, parcels or registered letters have to be delivered personally by the postman. It is a common perception that postmen sometimes do not even bother to ring the bell and just leave a notice on the door saying that the mail can be retrieved at some mail delivery center. Thus, they save on their time while increasing the workload at the center. They free-ride on their colleagues.

It is widely acknowledged that team production is 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).

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 between groups on within-group performance. In summary, surprisingly, little seems to be known on whether competition between teams eliminates free-riding as team members contribute sequentially.

The present study tries to shrink this gap in the literature with two contributions. We first develop a model where members of competing teams contribute sequentially to win a commonly shared prize. Secondly, we provide an empirical assessment of free-riding within teams when there is competition between teams.

Developing our model we draw on the literature on contests between groups, following Katz et al. (1990), Ursprung (1990), or Gradstein (1993) among others, who model competition between groups when group members contribute simultaneously.¹ Starting from these studies we delineate a model of competition between groups when team members contribute sequentially to the team. There is a prize for the winning team awarded to every team member. Higher costly efforts by any team member increases the probability for the team to win the prize, as team member efforts enter additively a Tullock contest function.

For testing our predictions we turn to swimming data. [**footnote moved down**] Typically, it is difficult to measure the performance of workers and their individual contribution to a team in standard work situations. 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

¹Two recent surveys are Corchón (2007) and Konrad (2009).

of natural experiments which allow for the testing of the effects of incentives on labour market behavior (Kahn, 2000; Szymanski, 2003).² Along these lines, 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.

Our comprehensive data-set 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 that team members moving earlier free-ride more. While external validity of results using sports data might be questioned, we believe that our empirical results in the context of teamwork make a particularly strong case. If free riding can be detected even in such contexts where output is perfectly measurable, its relevance in real life work situations where monitoring is more difficult is even more likely.

We proceed in the following way. In section 2 we set-up the theoretical model. In section 3 we present our empirical testing strategy, providing some background on the rules and main characteristics of swimming competitions and describing the data we use, while in section 4 we present and discuss our empirical results. In section 5 we conclude.

²However, existing 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).

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 cost $c(e)$. 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. In order 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 member 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 for second players, as is first players' effort. This amounts to say that second players observe first players' performance.

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.

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 of the random component on individual performance. 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. First players make their choices taking into account the later realization of ε , and the reaction of the second players in teams A and B , respectively.

Given that ε enters additively the CSF, its value does not affect the choices of second players. Furthermore, as players are homogeneous, everybody expects that simultaneous players will put the same effort. Imposing $e_{A1}^* = e_{B1}^*$ and $e_{A2}^* = e_{B2}^*$, as we will do in the following, greatly simplifies the derivation of the proofs.⁴

⁴The same results can be obtained without imposing symmetry. The proofs are available upon request.

For second players, effort choices follow from the first order conditions

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

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

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. Solving these first order conditions for the optimal choices e_{A2}^* and e_{B2}^* , ruling out the negative effort choices, yields

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

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

With second order conditions being fulfilled, e_{A2}^* and e_{B2}^* constitute the best choice of the team members moving second.

Equations (8) and (9) are the reaction functions 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. An increase of effort of the first player leads to a decrease in the teammate's effort. 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.

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 are

$$\frac{dV_{A1}}{de_{A1}} = \alpha \frac{(e_{B1} + e_{B2}) \left(1 + \frac{de_{A2}}{de_{A1}} - \frac{de_{B2}}{de_{A1}}\right)}{D^2} S - 2e_{A1} = 0 \quad (10)$$

$$\frac{dV_{B1}}{de_{B1}} = \alpha \frac{(e_{A1} + e_{A2}) \left(1 + \frac{de_{B2}}{de_{B1}} - \frac{de_{A2}}{de_{B1}}\right)}{D^2} S - 2e_{B1} = 0 \quad (11)$$

using $e_{A1}^* + e_{A2}^* = e_{B1}^* + e_{B2}^*$. Eqs. (10) and (11) determine the effort choices of first players. Again, expected marginal benefits have to equal the marginal costs which are a function of the effort of the first players. Compared to the first order conditions of the second players, the marginal benefits of the first players take account of the effect of the effort choice of the first player on the teammates choice coming after, and the second player's effort choice of the competing team.

Proposition 1 *In equilibrium, the optimal 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, $-1 < \frac{de_{A2}}{de_{A1}} < 0$, and $\frac{de_{B2}}{de_{A1}} = 0$ which implies that the choices of the first players do not have an impact on the other team's second player behavior. While the latter result is essentially driven by the symmetry of the set-up, the former is due to the substitutability of efforts within teams, as seen by the downward sloping reaction functions (8) and (9). 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. Now, we 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.*

Proof See Appendix A.

Intuitively, the cooperative solution takes into consideration that the prize S is non-rival and that effort exerted by any individual player has a positive externality on the other 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.

We can also show that second players choose an effort level which is lower than what a player chooses for an individual production. Moreover, effort choice for individual production is equal to the effort choice in a cooperative social optimum.

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 stems directly from the assumption that the prize S gives the same individual utility in both cases.

3 Data and testing strategy

3.1 Swimming competitions

Swimming competitions entail four competitive styles –backstroke, breaststroke, butterfly and freestyle– at varying distances (e.g. 100 meters, 200 meters, etc.) typically in 25 or 50 meter pools.⁵

Relays are a group of swimmers who either all swim freestyle 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

⁵Rules for these swimming competitions, may they be national or international, are set by the Federation Internationale de Natation (FINA) (www.fina.org).

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. 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 directly 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.

Various rules guarantee accurate measurement of swimmers' performances. Time keeping is under the supervision of appointed officials and 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.

3.2 Data description

Our data-set 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 we have 311,784 observations of performances of individual swimmers at more than 7,000 events which took place worldwide between 1972 and 2009. Due to our identification of individual ability by comparing a swimmer's performance in a relay with his performance in an individual competition, the data comprises athletes who took part in the same event and for the same style, both in the individual competition and in the relay.

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, see table 1.

As for the *personal characteristics* of the swimmers, we have information on age, gender, nationality, 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. The FINA Point Scoring assigns point values to swimming performances. Points are assigned at every competition, by comparing a swimmer's performance with a base time that is recalculated every year, taking the average of the top ten of the All Time World Rankings. More points go along with better performance. In the sample, FINA points are related to the individual competitions and vary between 5 and 1,181 with a median of 504. Michael Phelps had 1,063 in the year of the Olympic Games in Beijing.

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.

3.3 Empirical strategy

Our first target for empirical testing is Proposition 1, which suggests that we should be able to detect that exerted effort of players increase towards the end of the competition. In principle, no data on individual competitions are necessary to test this proposition, as it has implications only for the behavior of relay swimmers. However, swimmers are not allocated to a relay in random order: rather, better swimmers are generally placed in the final slot. This implies that later swimmers are on average faster, and attributing this better performance to lower free-riding would be incorrect. In order to overcome this problem, we use the information on each relay swimmers' performance in the individual competition to control for his/her ability: our dependent variable is therefore the relative difference in swimming time between the relay and the individual competition.

If Proposition 1 is of empirical relevance, we should find that this relative difference decreases towards the end of the relay competition. This result is independent of potentially different valuation of prizes between relay and individual competitions. It does not require the assumption of an equal valuation of the prize S .

Moreover, if we are willing to assume an equal valuation of the prize S , by Proposition 3 we can interpret the performance in the individual competition as the socially optimal level of effort in the relay, and measure the maximum extent of free-riding by comparing individual and relay swimming times, for the first players in the relay. ~~This can be done for first players only, as subsequent players enjoy an advantage in reaction time.~~ By Proposition 2, free-riding for subsequent players is reduced but not eliminated.

4 Empirical evidence

4.1 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. 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 for the first swimmers 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.

There are no indications that training or the use of illegal substances targeted to a specific competition (individual or relay) might disturb our results. In 87% of the observations individual and relay competitions are within 1 day of separation which implies 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 our result is also valid if we look into major events only.

As we have already noted, direct comparison between the relay and the individual competition is possibly 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. This explains why the time difference turns negative for the second to the fourth swimmers in the relay. More importantly, however, 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.

Summarizing these findings, faster swimming times for later swimmers in the relays provide evidence in support of our Proposition 1. Furthermore, if one is willing to accept the hypothesis of equally valuable prizes in the individual and the relay competition, the evidence presented for first swimmers is consistent with the implications of Propositions 2 and 3 of our theoretical model. In order to further elaborate on these findings we turn to a multivariate analysis which allows us to fully exploit our data-set.

4.2 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 com-

petition. Other controls are gender, age⁶, 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).

We expect the coefficient of the dummy variable for the first swimmer in the relay to be positive. Furthermore, we expect the coefficients for the dummy variables for subsequent swimmers to be negative because of the advantage in the reaction time for every swimmer following the first one. As later swimmers should on average exert more effort we also 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 percentage points, 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.

4.3 Robustness analysis

We control for individual ability by relating the relay performance of a swimmer to the performance of the same swimmer in the individual competition. Thus we have already dealt with the most important composition issue that more able swimmers might be placed in a later slot. Additionally, one might be concerned that some swimmers are more motivated than others in swimming a relay. If this was the case and team managers put more motivated athletes as last swimmers in the relay, first swimmers would be less motivated. This could explain slower performance even after controlling for individual ability.

In order to control for motivational and other (time invariant) unobservable

⁶We 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.

characteristics of our swimmers we introduce individual fixed effects (Model 2). Thus, we compare the difference one specific athlete scored between relay and individual time when starting the relay at a different order (at different events). For example, a swimmer might have participated at the Olympic Games and the World Championships for 100 m freestyle and the 4×100 meters freestyle as third and fourth swimmer, respectively. There should be no increase in the relative performance with respect to the individual race when he swam fourth, even if results are driven by unobservable characteristics. If, however, we still observe faster swimming times for later swimmers after canceling out unobservable individual characteristics, it would strengthen the finding of free-riding.

Running a fixed effects model yields a coefficient for the first order dummy (the constant) of .51.⁷ The coefficients for the other order dummies become -.71, -.78 and -1.03, respectively. Hence, the fixed effect model confirms our previous findings (and our theoretical model). Note that the number of observations drops to 107,808 as all records pertaining to swimmers for which there is no variation in the independent variables have to be dropped.

That free-riding is still prevalent as we use each swimmer's time in the individual competition as a control for individual ability and as we additionally run a fixed effect model may also be interpreted as supporting evidence for our modeling choice in the first part of the paper. We assumed that all swimmers have the same ability when deriving our propositions. If heterogeneous ability mattered then we should have seen that free-riding vanishes as we run fixed effects models on top of controlling for individual ability with swimming times of individual competitions. As it did not, we feel quite confident with the (simplifying) modeling choices made. Although heterogeneous ability is certainly given among the swimmers of the teams, it seems that team managers can not solve the free-riding problem by allocating swimmers to particular slots.

One could also 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. Therefore, we estimate our fixed effect model on finals only, both for

⁷This 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.

the relay and the individual competition (Model 3), on the assumption that finals are more competitive. 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. Due to the additional restriction, the number of observations drops to 25,138. The results still go through if we further restrict to swimmers ending up in the first four positions both in the relay and in the individual competition (the coefficients for the order dummies are, respectively, 1.26, -.94, -1.08, -1.52).

As a final robustness check, in order to reduce a further cause of unobserved heterogeneity, we estimate our fixed effect model on freestyle swimmers only. The results still go through (the coefficients for the order dummies are, respectively, .86, -.76, -.85, -1.25).

4.4 Size of the effects

For establishing a benchmark against which to evaluate the size for free-riding, we calculate the average lag in swimming time between individuals belonging to teams that finished in n th place in relays and individuals belonging to teams that finished in $n - 1$ th place, for $n > 1$. On average this lag is .23% for major events and 1.35% for non-major events among the first 10 positions in the final ranking. These numbers may now be compared to the size of free-riding as shown in table 2 and 3. In table 2 we calculated for first swimmers at a major event 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%. In table 3 (Model 2) we get an effect that is even more relevant: athletes in our reference category are on average .51 percentage points slower in relays than in individual competitions compared to an average lag to an immediately preceding team of .78 percentage points 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 ta-

ble 3. Comparing the estimated effect of the fourth swimmers with the third swimmers yields a reduction in free-riding of $1.03 - .78 = .25$ percentage points. This value must again be compared with an average lag over the preceding team of .78 percentage points, 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 percentage points, 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 show that in such a setting there is free-riding among team members. ~~even under competition between teams.~~ We also show 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 observations from swimming 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 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 in the in-

dividual race as a control we find that on average these swimmers swim slower in relays. Moreover, controlling for reaction times and individual effects we find that free-riding diminishes as we move from the second, to the third and finally the fourth swimmer in the relays. Results are robust against including various controls. Furthermore, the estimated time differences occur to be of meaningful size.

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.⁸ 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. The difference 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* teams, and that this free-riding is stronger for early contributors (Proposition 1), 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, neither competition nor an almost ideal monitoring system solve the free-riding problem, our results point to the necessity of devising better incentive mechanisms.

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⁸The other side of 'two in distress make sorrow less'.

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Appendix A

Proposition 1

Proof The proof is in two parts. In part (I) we show that the f.o.c. define the optimal effort level for players 1 as the s.o.c. are also satisfied. In part (II) we show that the optimal effort level for players 1 is lower than the optimal effort level for players 2.

Part I:

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

$$\frac{d V_{A1}}{d e_{A1}} = \alpha \frac{(e_{B1} + e_{B2}) \left(1 + \frac{d e_{A2}}{d e_{A1}} - \frac{d e_{B2}}{d e_{A1}}\right)}{D^2} S - 2e_{A1} = 0. \quad (13)$$

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

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

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

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

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

Rewriting in matrix form yields

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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 by inserting terms into eq. (18) we get

$$\frac{d e_{B2}}{d e_{A1}} = 0. \quad (34)$$

Hence the s.o.c. simplifies to

$$\frac{d^2 V_{A1}}{d e_{A1}^2} = \alpha(e_{B1} + e_{B2}) \frac{D(\frac{d^2 e_{A2}}{d e_{A1}^2} - \frac{d^2 e_{B2}}{d e_{A1}^2}) - 2(1 + \frac{d e_{A2}}{d e_{A1}})^2}{D^3} S - 2. \quad (35)$$

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 (35) and further rearranging yields

$$\frac{d^2 V_{A1}}{d e_{A1}^2} = \alpha \frac{2S}{D^2} (\alpha \frac{S}{D^2} - 6) - 8 \quad (36)$$

which is negative if

$$\alpha \frac{S}{(2e_{A1} + 2e_{A2})^2} < 6. \quad (37)$$

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.

Part II:

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

$$-1 < \frac{d e_{A2}}{d e_{A1}} - \frac{d e_{B2}}{d e_{A1}} < 0 \quad (38)$$

which follows from the comparison of the f.o.c. of the first and second players. We already know that $\frac{d e_{B2}}{d e_{A1}} = 0$, see eq. (34), 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:

$$c'(e_{A2}) = 2e_{A2} = \alpha \frac{S}{4(e_{A1} + e_{A2})} \quad (39)$$

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

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

$$V_A = 2p_A S - e_{A1}^2 - e_{A2}^2. \quad (40)$$

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

$$\alpha \frac{2(e_{B1} + e_{B2})}{D^2} S - 2e_{A2} = 0 \quad (41)$$

$$\alpha \frac{2(e_{B1} + e_{B2})}{D^2} S - 2e_{A1} = 0. \quad (42)$$

Symmetry then implies

$$2e_{A1} = 2e_{A2} = \alpha \frac{S}{2(e_{A1} + e_{A2})} = \alpha \frac{S}{4e_{A2}} \quad (43)$$

which is higher than the effort exerted by the second player in the non-cooperative solution given by (39).

Proposition 3

Proof From equation (39), absent player 1, player 2's optimal effort would be determined by:

$$c'(e_{A2}) = 2e_{A2} = \alpha \frac{S}{4e_{A2}} \quad (44)$$

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 at major events):	(3,835)	
Olympic games	660	
World championships	1,531	
European championships	766	
Pan Pacific games	390	
Commonwealth games	184	
Universiades	304	
	Major	Non-major
Style		
50m Breaststroke	-	20,092
50m Fly	-	17,619
50m Freestyle	7	103,079
100m Breaststroke	704	28,015
100m Fly	734	24,450
100m Freestyle	1,528	94,506
200m Freestyle	862	20,188
Schedule		
individual first ^(a)	2,629	78,196
relay first ^(b)	935	82,357
same day	271	147,396
Round (individual competition)		
timed finals (default)	21	144,415
finals	902	74,960
semi-finals	517	2,113
preliminaries	2,390	86,206
others ^(c)	5	255
Round (relay)		
timed finals (default)	342	202,042
finals	1,569	93,238
preliminaries	1,924	12,101
others ^(c)	-	568
Order (relay)		
1st	659	65,892
2nd	1,172	87,421
3rd	1,086	78,918
4th	918	75,718
...		

... table 1 continued

Gender

male

2,096

153,245

female

1,739

154,704

Age: median [min-max]

21 [13-52]

16 [6-109]

FINA points: median [min-max]

846 [64-1093]

501 [5-1181]

(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 preliminaries

Table 2: Comparing individual and relay swimming times only

	Swimming times					
	Individual (secs.) I	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