Market Concentration and Incentives to Collude in Cournot Oligopoly Experiments*

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Abstract

We study why smaller groups tend to become more collusive in Cournot oligopoly experiments. We show that theoretically, the group size effect could be explained by the changes in incentives and salience. We then propose a new experimental design in which the incentives and salience are invariant to group size. In this setup, we find that the group size has no direct effect on the average output or profit. We conclude that the previously observed group size effect is driven by the changes in incentives or salience rather than by the number of firms itself.

Keywords: experiment, oligopoly, collusion, group size, Quantal Response Equilibrium

JEL classification: C72 C91 D43 D83

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1 Introduction

The determinants of tacit collusion in oligopolies have been studied since the very onset of experimental economics (see Sauermann and Selten, 1959, and Fouraker and Siegel, 1963). One robust finding from this literature is that markets with fewer firms tend to become more collusive (Huck et al., 2004, Horstmann et al., 2018). However, the previous literature did not study whether the group size effect is driven by easier coordination among fewer firms, or because in such markets each firm has more individual incentives to restrict output. We demonstrate the viability of the incentive-based explanation by showing that in smaller groups, firms have weaker incentives to deviate from collusive agreements and bounded rationality predicts more collusive behavior. We test this prediction by designing and running a Cournot oligopoly experiment in which the incentives to collude and the salience of choices are invariant to group size. By comparing the group size effect in our new design to the standard Cournot treatments, we can identify whether the group size effect is driven directly by the number of firms, or instead by the changes in incentives or salience that go with it.

Understanding whether collusion is driven by the group size itself ("coordinated effects") or by the changes in incentives ("unilateral effects") or salience is important for regulators to identify the potentially collusive markets and assess the consequences of antitrust policies (Levenstein and Suslow, 2006). Up until the end of the twentieth century, regulators aimed to curb market concentration, measured either by the number of significant competitors in the market or using the Herfindahl-Hirschman Index.[1] Recently, the focus shifted towards the economic factors that affect the incentives to collude (Shapiro, 2010) and it has been debated whether an indicator of upward pricing pressure should replace the concentration-based methods (Farrell and Shapiro, 2010; Jaffe and Weyl, 2013). When making a recommendation on whether mergers should be screened based on coordinated or unilateral effects, regulators need to know whether market concentration facilitates collusion. Since obtaining empirical data about collusion is difficult (Davies et al., 2011), some regulators started to rely on experimental evidence. For example, the UK regulator recently suggested that more attention should be paid to coordinated effects, based partly on the recent experimental evidence (Olsen and Schwarz, 2022).[2] Identifying whether collusion is driven purely by the group size would help the regulators

[1]See Davies et al. (2011), Farrell and Shapiro (1990) and U.S. Department of Justice & Federal Trade Commission, Horizontal Merger Guidelines (2010), available at http://www.justice.gov/atr/public/guidelines/hmg-2010.pdf

[2]In the most recent 2021 version of the Merger Assessment Guidelines, the Competition and Market Authority (CMA) added that "coordinated effects have been considered by the CMA relatively infrequently in the past", but CMA is considering to strengthen enforcement in that area due to evidence that "coordination in concentrated markets is common and has the effect of restricting competition and raising prices". As evidence, CMA cites Baker and Farrell (2020) who in turn draw the conclusion about the small number of firms facilitating collusion in large part based on the experimental economics literature.

decide whether they should strive to keep markets unconcentrated, or instead focus on measuring and limiting the incentives to collude.

In the experimental treatments that were designed to keep the incentives and salience invariant to the group size, we find that the group size has no effect on the aggregate measures of collusion. In contrast, treatments that used the standard Cournot payoff function reproduced the common pattern of more collusion in smaller groups. We therefore conclude that the group size effect, documented in the previous literature, is not driven by easier coordination in smaller groups. Our results suggest that antitrust policies that limit market concentration might fail to increase competitiveness, and regulators might have rightly switched to assessing how mergers change the incentives to collude.

Although group size does not affect average output or profits, we find greater variance of output in smaller groups, thus more choices are classified as collusive – but also as competitive. Interestingly, this effect is not found in the treatments with the standard Cournot payoff function. The difference could be explained by how the output of the opponents is aggregated. In our normalized treatments, payoffs depend on the average output of other firms, which is more stable in markets with many firms and thus choosing very high or very low output rarely maximizes profits. The change in stability does not occur in standard Cournot treatments, where payoffs depend on the total output that does not become more stable in larger groups. We formalize these arguments by developing a modified version of QRE, in which choice probabilities depend on the likelihood that an action is the best response. We show that this solution concept fits data better than QRE and can explain increased variance in smaller groups.

Our study extends the results from the previous experiments in Cournot oligopoly, where output is typically found to be more collusive in markets with fewer firms. Fouraker and Siegel (1963) found slightly more collusive behavior in Cournot duopolies than in triopolies. Huck et al. (2004) found that average output is more collusive and more markets are classified as collusive in duopolies than quadropolies. Roux and Thöni (2015) replicated these results in baseline treatments without punishment. Waichman et al. (2014) found a higher frequency of collusion counts in duopolies than in triopolies when communication was not possible, although the effect was not significant in the manager sample. Similarly, Fonseca et al. (2018) found an increase in the collusiveness of output when the number of firms decreased from six to four and from four to two, in treatments without communication. In quadropolies without a forward market, output was more competitive than the equilibrium prediction, but more collusive than equilibrium in duopolies (Le Coq and Orzen, 2006). Van Koten and Ortmann (2013) also ran baseline treatments without a forward market and found that output was more competitive than the equilibrium prediction in quadropolies, but not in triopolies or duopolies. Horstmann et al. (2018) found that duopolies were more collusive than triopolies, which in turn were more collusive than quadropolies, as measured using two collusion indexes. Horstmann et al.

(2018) also performed a meta-analysis of previously published results and found higher rates of tacit collusion in duopolies than in triopolies or quadropolies.[3]

Increased collusiveness in smaller groups is also found in Bertand oligopoly experiments. Fouraker and Siegel (1963), Dufwenberg and Gneezy (2000), Orzen (2008), Davis (2009) and Fonseca and Normann (2012) found less competitive behavior and higher profits in Bertrand duopolies, compared to triopolies or quadropolies. A meta-analysis and additional experiments in Horstmann et al. (2018) corroborate these results.

More generally, we contribute to the recent experimental literature that studies how behavioral regularities depend on the number of interacting participants (Diederich et al., 2016, Choi et al., 2020, Arifovic et al., 2022). We contribute to this research by designing a method to identify the mechanism behind the group size effect, which needs to be understood to draw policy implications from this line of research. We show that group size can change the incentives in a non-trivial way, which can be modeled using models of bounded rationality and controlled using a payoff function that keeps the incentives similar across different group sizes. We are aware of only one other paper that studied the mechanism behind the group size effect: Isaac and Walker (1988) noticed that in public goods games, an increase in group size would decrease the marginal per capita return of contributions to a public good. A change in the group size could therefore be divided into a "pure" group size effect and the part of the effect driven by the changes in incentives to contribute. Isaac and Walker (1988) observed a significant decrease in contributions when the group size was increased from 4 to 10. However, the effect disappeared when the payoff function was corrected to keep MPCR constant across group sizes.[4] Similarly, we find a decrease in the group size effect in Cournot oligopoly when the payoff function is normalized to keep the incentives comparable.

The rest of the paper is organized as follows. Section 2 presents our design: payoffs and theoretical predictions in Cournot oligopoly (Section 2.1), discussion of the mechanism behind the group size effect (Section 2.2), design of the normalized treatments and how they differ from standard treatments (Section 2.3) as well as other implementation details (Section 2.4). Section 3 shows how the Quantal Response Equilibrium can be used to measure the differences in incentives to collude and finds that a decrease in group size increases such incentives in the standard treatments, but not in the normalized ones. Section 4 presents the results of the experiment: in standard treatments, we replicate the results from previous literature, but in the normalized treatments, we do not find that

[3]A slightly different design was used by Friedman et al. (2015), who compared Cournot duopolies to triopolies with a unit elastic demand function in a low information environment and 1200 4-second rounds. By the end of the game, output converged to the collusive outcome in the duopoly, but not in the triopoly. Oechssler et al. (2016) replicated the study using a standard linear demand function and found more collusive behavior in duopolies than in quadropolies.

[4]Follow-up studies found that the group size may have a significant effect, although it depends on the value of MPCR and the nature of the game; for example, see Isaac et al. (1994), Barcelo and Capraro (2015), Nosenzo et al. (2015), Zelmer (2003).

smaller groups become more collusive (Section 4.1), although in these groups we observe increased variance of output (Section 4.2). Section 5 attempts to explain these results, showing that QRE can explain the results about the average output, but not the change in the variance (Section 5.1), which can instead be explained by a modification of QRE that takes into account the best-response likelihood (Section 5.2). Section 6 concludes and discusses the implications of our results for competition policy and for the research on the group size effects.

2 Experimental Design

2.1 Payoffs and Key Outcomes

We study a symmetric n-firm Cournot oligopoly. Each firm $i \in N$ simultaneously chooses output q_i. Price p_i is determined by a linear inverse demand function:

$$p_i(q_i, q_{-i}) = \max\left(0, 81 - \left(q_i + \theta \sum_{j \in (N \setminus i)} q_j\right)\right) \tag{1}$$

where q_{-i} denotes the vector of outputs by firms other than i.

The sole difference compared to the standard Cournot oligopoly implementation (e.g. Bigoni and Fort, 2013, Huck et al., 2004) is the addition of θ, which could be interpreted as the degree of product differentiation (Vives, 1984, Horstmann et al., 2018). If $\theta = 1$, as is commonly assumed, products are homogeneous and the market price is common for all firms.

We assume that the marginal cost of production is equal to one, so that the cost function is $C(q_i) = q_i$. We also added a fixed cost (FC) and scaled the payoffs using parameter s to make the games with different group sizes more comparable with each other. Then profits earned by i are:

$$\pi_i(q_i, q_{-i}) = (p_i(q_i, q_{-i})q_i - q_i)s - FC$$

Three key outcomes are typically studied in Cournot oligopoly games: collusive outcome, at which the sum of payoffs earned by all players is maximized; Nash equilibrium, at which all players best-respond to the action profile of everyone else and Walrasian equilibrium, at which all players maximize their relative profits. We calculate the symmetric outcomes of interest using the standard procedure. Individual output in a symmetric Nash equilibrium is $q_i^N = \frac{80}{2+\theta(n-1)}$, in a symmetric collusive outcome it is $q_i^C = \frac{80}{2+2\theta(n-1)}$ and in a symmetric Walrasian equilibrium[5] it is $q_i^W = \frac{80}{1+\theta(n-1)}$. There sometimes are

[5] With the parameters used in the experiment, the Walrasian equilibrium is at the point where price equals marginal cost. In general, the symmetric relative payoff maximization point could be different for

asymmetric collusive outcomes and asymmetric Nash equilibria; in all asymmetric Nash equilibria, the total output is equal to the total output produced in the symmetric equilibrium.[6]

2.2 Group Size Effect

We designed the experiments to clarify the mechanism behind the group size effect observed in the previous Cournot literature. Based on the previous findings and the insights from competition policy, we identify three potential mechanisms that could explain why output is more collusive in smaller groups:

1. **In smaller groups, it is easier to coordinate.** Regulators seek to limit market concentration partly due to a belief that "the presence of many competitors tends to make it more difficult to sustain coordination (...)".[7] This belief is supported by the results from economic experiments. Smaller groups manage to coordinate on higher prices and receive higher profits in Bertrand oligopoly (Dufwenberg and Gneezy, 2000; Davis, 2009; Fonseca and Normann, 2012), coordinate on the efficient equilibrium in a minimum effort game (Van Huyck et al., 1990) and sustain cooperation in voluntary contribution mechanism games (Nosenzo et al., 2015). The success of smaller groups could be explained by the use of "language of coordination" (Davis, 2009), which allows participants to signal their intentions to collude and identify deviations from collusive agreements (Masiliūnas, 2017). We call this explanation the "pure group size effect" (following Isaac and Walker, 1988), as it is driven directly by the group size, rather than by the change in incentives or other elements of the game.

2. **In smaller groups, there are more incentives to collude or less incentives to deviate from collusive agreements.** In competition policy, mergers are expected to increase the individual incentives to increase prices, commonly measured using the value of diverted sales or an index of upward pricing pressure (Shapiro, 2010, Farrell and Shapiro, 2010). This "unilateral effect" is typically explained by the merged firm having more incentives to raise prices because some of the sales lost due to a higher price can be recaptured by selling more substitute products (Jaffe

small values of θ, i.e. if $\theta(n-1) < 1$.

[6]In the normalized treatments with the parameters used in the experiments and a discrete strategy space, there are 4 asymmetric equilibria in markets with two firms: (7,9), (9,7), (0,16), (16,0). There are 18 asymmetric equilibria in markets with three firms and 18 in markets with four firms. The average output is the same in all equilibria. Multiplicity of equilibria is common in a Cournot oligopoly: for example, in the standard treatments, there are 2 asymmetric equilibria in two-firm markets, 6 equilibria in three-firm markets and 18 equilibria in four-firm markets.

[7]U.S. Department of Justice & Federal Trade Commission, Commentary on the Horizontal Merger Guidelines (2006), available at http://www.justice.gov/atr/public/guidelines/215247.pdf. Also see Ivaldi et al. (2007).

and Weyl, 2013). A similar effect is present in Cournot oligopoly, where firms in larger groups have more incentives to deviate from the collusive agreements. The incentives to collude are commonly compared using the Friedman index, which is connected to the minimum discount factor needed to sustain collusion in an infinitely repeated game (Friedman, 1971). The index predicts that collusive agreements should be more stable in smaller groups, due to less incentives to deviate from such agreements. Our experiment follows the previous literature and uses finitely repeated games, therefore collusive equilibria do not exist; however, we use the Quantal Response Equilibrium predictions to show that changes in incentives still predict more collusive output in smaller groups.

3. **In smaller groups, more choices are classified as collusive because the collusive outcome is closer to the salient options.** Preferences and beliefs depend on the choice set and item's location in the set; for example, there is a preference for options in the middle (Valenzuela and Raghubir, 2009; Chang and Liu, 2008) or for the multiples of 10 or 100. In standard Cournot oligopoly, the salience of the key outcomes, their location on the strategy space and the distance between them change in response to the group size. These changes could affect the behavior of boundedly rational participants and therefore more choices might be misclassified as collusive in smaller groups.

2.3 Treatments

We separate the pure group size effect from the explanations based on incentives or salience by comparing the effect in "standard" Cournot treatments to "normalized" treatments, where the incentives and salience do not vary with group size. We expect that the standard treatments will replicate the well-known finding of more collusive output in smaller groups, and test whether the group size effect is reduced in normalized treatments. We used the same subject pool and experimental procedures in all treatments to ensure that the differences are not driven by other factors.

In total, we ran two standard treatments (with the group size of 2 and 4) and three normalized treatments (with the group size of 2, 3 and 4). The additional three-group treatment was added to better understand the group size effect in the novel normalized design. Table 1 summarizes the key differences between the five treatments. The main difference between standard and normalized treatments lies in how the output of the opponents is aggregated, which is determined by the θ parameter. In standard treatments, we set $\theta = 1$, regardless of the group size, as is common in the previous literature (e.g. Huck et al., 2004, Roux and Thöni, 2015, Horstmann et al., 2018, Oechssler et al., 2016). As a result, a change in the group size does not affect the profit of firm i if the output

Table 1: Parameter values (n, θ, s, FC), strategy space, output in the three key outcomes (collusive outcome, Nash equilibrium and Walrasian equilibrium), payoffs in these key outcomes (in ECU), incentives to collude (Friedman index) and the number of observations in the experiments (number of participants and markets) in each treatment.

Treatment	S2	S4	N2	N3	N4
n	2	4	2	3	4
θ	1	1	3	1.5	1
s	0.36	1	1	1	1
FC	-130	-130	-130	-130	-130
Strategy space	0-50	0-50	8-24	8-24	8-24
q_i^C	20	10	10	10	10
q_i^N	26.67	16	16	16	16
q_i^W	40	20	20	20	20
$\pi(C)$	418	530	530	530	530
$\pi(N)$	386	386	386	386	386
$\pi(W)$	130	130	130	130	130
Friedman index	0.89	0.64	0.64	0.64	0.64
# participants	36	60	96	72	96
# markets	18	15	48	24	24

of firm i and the *sum* of output of all other firms are held constant.[8] In normalized treatments, we set $\theta = \frac{3}{n-1}$, therefore the group size does not affect the profits of i if the output of i and the *average* output of all other firms are held constant. This small difference in the aggregation of opponents' output has important consequences on how the incentive structure responds to changes in group size.

In the standard treatments, group size affects the output and payoffs in the three key outcomes: Nash equilibrium, collusive outcome and Walrasian equilibrium. The first two columns of Table 1 summarize these differences in treatments with two and four firms (S2 and S4). Nash equilibrium payoffs are held constant using a scaling parameter ($s = 1$ in S4, $s = 0.36$ in S2), but the payoffs in the collusive outcome and the most profitable deviation from it are different. The incentives to collude are commonly measured using the Friedman index (Friedman, 1971), defined as $F = \frac{\pi(C)-\pi(N)}{\pi(D)-\pi(C)}$, where $\pi(D)$ is the payoff from the most profitable unilateral deviation from the collusive outcome. Friedman index shows that a larger group size reduces the incentives to collude in the standard treatments, but not in the normalized treatments,[9] where the payoffs at each outcome and the locations of these outcomes are invariant to group size.

The second difference between standard and normalized treatments is in the strategy space. In standard treatments, firms could choose output from 0 to 50. In normalized treatments, the strategy space was restricted to 8-24, for several reasons. First, we wanted

[8]Note that the payoffs are held constant by appropriately setting the s parameter in the two treatments.

[9]Friedman index values in our experiment are identical to the values in standard experiments that manipulated group size in Cournot oligopoly, e.g. Huck et al. (2004).

to evenly space out the three key outcomes across the strategy space to improve the accuracy of categorization. If all three outcomes are located at the bottom of the strategy space (e.g. as in S4), there is more scope for exceeding the equilibrium prediction and we might underestimate the degree of collusion. Instead, in normalized treatments, the Nash equilibrium was placed in the middle of the strategy space and the other two outcomes were located at a similar distance from it. Furthermore, none of the key outcomes were located at the either end of the strategy space, so as not to misclassify extreme choices as either perfectly collusive or perfectly competitive. It was also necessary to bound the strategy space from below to decrease the possibility of collusion by an alternating play of asymmetric outcomes.[10]

Finally, the strategy space in normalized treatments was labeled such that the key outcomes would not be salient. For example, in S4 treatment, the collusive and competitive outcomes are at salient locations (respectively 10 and 20), and previous studies that used the same parametrization found that these outcomes are commonly chosen (Bigoni and Fort, 2013). It is unclear whether these values were chosen because they were salient, or because participants converged to the collusive or competitive outcome. To simplify the explanation of the game and reduce the salience of the key outcomes, we re-labeled the strategy space, using numbers 0-16 to represent output 8-24. The mapping was performed in two ways: in "increasing" treatments, higher output was represented by higher numbers in the strategy space (i.e. output of 8 was labeled as "0" and 24 was labeled as "16"). In "decreasing" treatments, higher output was represented by lower numbers (i.e. output of 8 was labeled as "16" and 24 was labeled as "0"), reversing the strategy space. This labeling ensures that the key outcomes are never at salient locations (in increasing treatments, key outcomes are at 2, 8 and 12; in decreasing treatments they are at 4, 8 and 14). Running the some treatments with a reversed strategy space helps to further evaluate the importance of salience and to eliminate its effect when classifying choices (for more details, see Appendix A).[11] In the data analysis section, we map the choices made by participants back into the output of the original Cournot payoff function and

[10]In N2, the symmetric collusive outcome is (10,10), generating a payoff of 530 ECU per firm. However, total payoffs would be maximized in the output profile (8, 16), with an average payoff of 546 EU per firm. In N3, the asymmetric collusive outcome is (8, 8, 16), with a profit of 535.33 EU per firm. In N4, all output profiles in which total output equals 40 generate the same payoff of 530 ECU per person. If the strategy space was not bounded from below, the payoff difference between symmetric and asymmetric collusive outcomes would be much larger, and cause different patterns of behaviour in markets with two and four firms. For example, the asymmetric collusive outcome in an unbounded two-firm treatment is (4, 24), with a payoff of 810 ECU per person. The lower limit of 8 makes the asymmetric collusive outcome less attractive, while keeping the symmetric collusive outcome in the interior of the strategy space. To completely eliminate the asymmetric collusive outcome, the lowest available output would have to be 10. In the data, we do not observe any successful attempts of asymmetric collusion.

[11]We find evidence that salient outcomes are more commonly chosen. For example, action labeled as "10" is the most commonly chosen action in N3I (increasing treatment with a group size of 3), second most common in N4I and N3D, third most common in N2I, N2D and N4D. When the same action is labeled as "6", it is chosen less than half of the time. If we hadn't run the treatments with a reversed strategy space, the frequency of competitive outcomes would likely be overestimated.

pool increasing and decreasing treatments.

2.4 Other Design Details

The stage game was repeated 20 times under partner matching. An alternative random matching protocol would have made it very difficult to study collusion. Each participant had 30 seconds to make a decision in each round (as in Bigoni and Fort, 2013). If no decision was made within the time limit, the output chosen in the previous round was implemented. If no decision was made in the first round, output was randomly drawn from a uniform distribution.[12]

The original instructions were in French; Appendix E provides a complete English translation. Instructions were identical in all treatments and framed using neutral language.[13] Participants could learn about the incentive structure using either a payoff table or a payoff calculator (examples of the information seen by the participants are displayed in figures G.1 and G.2 in Appendix G). The payoff table listed participant's payoffs for some combinations of chosen output and the average output of the opponents: 441 combinations in standard treatments (21x21 action profiles, 0-50 in increments of 2.5) and 289 combinations in normalized treatments (17x17 action profiles, 0-16 in increments of 1). The payoff calculator could be used to compute the payoff for any combination of own output and the average output of the opponents.

In each round other than the first one, participants had access to two additional tools. The "output-payoff graph" visually displayed the previous round output-payoff combinations of all participants in the group (see Friedman et al., 2015 for a similar design). This information is needed for the imitate-the-best dynamics, which converges to the Walrasian equilibrium (Vega-Redondo et al., 1997). The second tool was a table that listed the history of player's chosen output and payoffs, as well the average output of the other group members in all previous rounds. This information is needed to make decisions from experience (e.g. reinforcement or belief learning). Participants could switch between the four tools at any time, and we tracked how much time was spent using each tool, just as in Bigoni and Fort (2013). This process data provides additional insight into how the decision making process is affected by the group size.

We set the fixed cost to $FC = -130$, providing a subsidy that prevents negative payoffs and generates positive payoffs in the Walrasian equilibrium.[14] We used the s

[12] The decision was not made within the time limit 3.5% of the time, primarily in the first two rounds. In the analysis part, we use all the decisions, although excluding the decisions that were not made explicitly does not change the overall results.

[13] For a discussion about how the use of neutral language rather than the more commonly used economic framing affects preferences and beliefs in Cournot oligopoly, see Masiliūnas and Nax (2020).

[14] The choice of the scaling parameters and the strategy space also ensure that in the normalized treatments all the payoffs are three-digit numbers (i.e. within the range 100-999), therefore no part of the payoff space is particularly salient.

parameter to scale the payoffs to equalize equilibrium payoffs across games with a different number of firms (see Table 1). In previous research, a change in equilibrium payoffs due to a different group size was corrected using different exchange rates (e.g. Huck et al., 2004, Bosch-Domènech and Vriend, 2003). Instead, we use an explicit scaling parameter to increase the transparency and keep the payoffs in the same order of magnitude across treatments, preventing any treatment effects due to the salience of payoffs.

After 20 rounds, participants continued the experiment with different games for another 20 or 40 rounds (depending on the treatment). This data was collected to study learning transfer and is used in a separate paper. Table D.1 in Appendix D shows the structure of the entire experiment. In this paper, we use only choices from the first 20 rounds. Participants were aware that the experiment will contain multiple parts, but did not know how many parts there will be and what type of games will be played. In each part, participants were matched with different opponents, therefore they never interacted with their opponents from the first part again. One round from each part was randomly selected at the end of the experiment, and the earnings from these rounds were added up and paid in cash.[15]

Additional information was collected at the end of the experiment. We elicited social preferences using the Social Value Orientation slider measure (Murphy et al., 2011, using the z-Tree implementation by Crosetto et al., 2019). We also measured the cognitive abilities using a part of the advanced version of Raven's Progressive Matrices task (Raven and Court, 1998). In this test, participants had 10 minutes to solve 16 tasks. After these tasks, we collected the age, gender and year of study of the participants.

In total, 360 participants took part in the experiments. The number of participants and markets in each treatment is shown in Table 1. In normalized treatments, exactly one half of the participants in each treatment took part in "increasing" treatments and the other half in "decreasing" treatments. We collected more observations for the normalized treatments because the standard treatments have already been studied in the previous literature.

All experiments were run in the LEEN laboratory of the Université Côte d'Azur in May and October 2018. The experiments took on average 75 minutes and participants on average received 14.2 euros. Participants were recruited using ORSEE (Greiner, 2015) and experiments were programmed using z-Tree (Fischbacher, 2007).

3 Quantal Response Equilibrium Predictions

We have shown that the normalization of the payoff function equalizes the payoffs in the three key outcomes. In this section, we further quantify the predicted group size effect in

[15]Earnings were denominated in ECU and exchanged to cash using rate 150 ECU = 1 euro.

the standard and normalized treatments. We model bounded rationality using Quantal Response Equilibrium (McKelvey and Palfrey, 1995), which is sensitive to the incentives and the locations of outcomes.

QRE requires consistency between actions and beliefs, but the responses to beliefs are noisy, therefore all actions are chosen with positive probability. In a game with n players, a set of players N, and a set of pure strategies $Q_i = \{q_1, \ldots, q_m\}$, denote the set of all probability measures on Q_i by Δ_i and the set of all probability measures on $\times_i Q_i$ by $\Delta = \times_i \Delta_i$. We will use shorthand notation $p = (p_i, p_{-i})$ for any $p \in \Delta$, where p_i is the mixed strategy of player i and p_{-i} is the mixed strategy profile of all other players. The probability with which player i chooses action q_k is $p_i(q_k)$. The expected payoff that i obtains by choosing q_k is denoted by $\pi_i(q_k, p_{-i})$. Nash equilibrium assumes that each player chooses the action with the highest expected payoff. Instead, QRE assumes that participants are maximizing their decision utility $u_i(q_k, p_{-i})$, equal to the sum of the expected payoff and the noise term:

$$u_i(q_k, p_{-i}) = \pi_i(q_k, p_{-i}) + \varepsilon_{ik} \tag{2}$$

If each of the stochastic terms ε_{ik} is independently drawn from a type-I extreme value distribution with parameter λ (McFadden, 1981) and each player chooses the action that generates the highest decision utility, the probability that i will play q_k can be calculated using a noisy best-response function $\sigma_i(q_k, p_{-i})$, defined as:

$$\sigma_i(q_k, p_{-i}) = \frac{e^{\lambda \pi_i(q_k, p_{-i})}}{\sum_{q_j \in Q_i} e^{\lambda \pi_i(q_j, p_{-i})}} \tag{3}$$

The logit QRE is a probability distribution $p \in \Delta$ that satisfies $p_i(q_k) = \sigma_i(q_k, p_{-i})$, for all $i \in N$ and $q_k \in Q_i$ (McKelvey and Palfrey, 1995). In other words, QRE requires the mixed strategy of each player to be a noisy best-response to the mixed strategy profile used by all other players.

Parameter λ measures precision, or sensitivity to expected payoff differences. If $\lambda = 0$, all actions are chosen with equal probabilities. A positive λ indicates that actions that generate higher expected payoffs are chosen more often. If $\lambda \to \infty$, there is no error and players always choose the action with the highest expected payoff, therefore QRE reduces to the Nash equilibrium.

Since the closed-form expressions of logit QRE are generally unknown, we calculate QRE using the tracing procedure from Turocy (2005), implemented using Gambit software (McKelvey et al., 2015). The calculations are performed using a discretized strategy space of 51 strategies (0, 1, . . . , 50) in standard treatments and 17 strategies (8, 9, . . . , 24) in normalized treatments. Payoffs used in the calculations are converted into monetary euro amounts (in experiments, the exchange rate was 150 ECU = 1 euro).

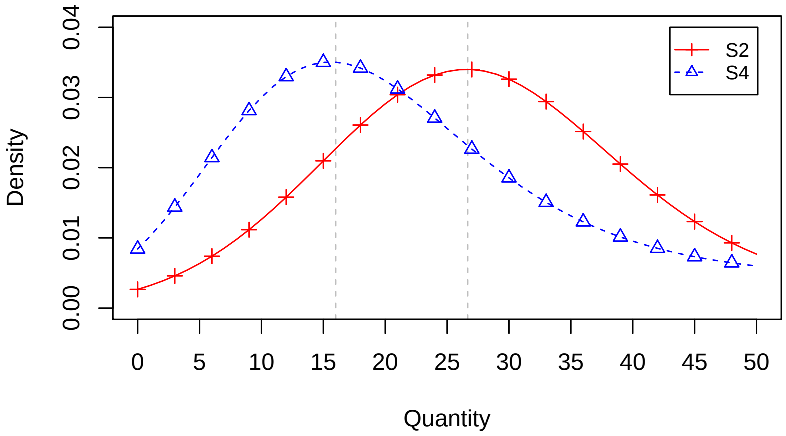


Figure 1: QRE distribution with $\lambda = 1.5$ in standard treatments. Vertical dashed lines indicate Nash equilibrium in S4 (16) and S2 (26.7).

3.1 QRE in Standard Treatments

We start by evaluating how QRE predictions respond to changes in group size in standard treatments and move to the normalized treatments in Section 3.2. First, we illustrate the QRE predictions by calculating the choice probabilities for a specific value of the precision parameter ($\lambda = 1.5$, which is close to the value in the best-fitting QRE model estimated in Section 5.1) and then show how these predictions change in response to the precision parameter.

Figure 1 shows the calculated QRE probability distributions in treatments S2 and S4. Both distributions are centered around the Nash equilibrium, but more choices exceed the Nash equilibrium prediction in S4 than in S2 (59%, compared to 51%), largely because the equilibrium prediction is lower in S4 than in S2 (16 instead of 26.7), thus there are more actions above than below it. Consequently, the average QRE output is much higher than the Nash equilibrium in S4 (20.6, compared to 16) but is very close to it in S2 (26.8, compared to 26.7).

We quantify the degree of collusion using two measures, and compare them across a range of the precision parameter. The first measure is the ratio of average output to Nash equilibrium output (Huck et al., 2004), calculated as $r = \frac{\hat{q}(\lambda)}{q^N}$, where $\hat{q}(\lambda)$ is the average output in a QRE with parameter value λ, and q^N is the Nash equilibrium prediction. Figure 2 plots r in S2 and S4 for values $\lambda \in [0, 10]$. If the sensitivity to payoff differences is high, QRE approaches Nash equilibrium and thus $r \to 1$. If the sensitivity is low, average output is below Nash equilibrium in two-firm markets and above it in four-firm markets, predicting more collusive output in markets with fewer firms.

The second measure is the frequency of collusive or competitive choices. We follow a common procedure (e.g. see Huck et al., 2004) and classify chosen output by the closest key outcome. Specifically, we partition the strategy space into actions that have the lowest

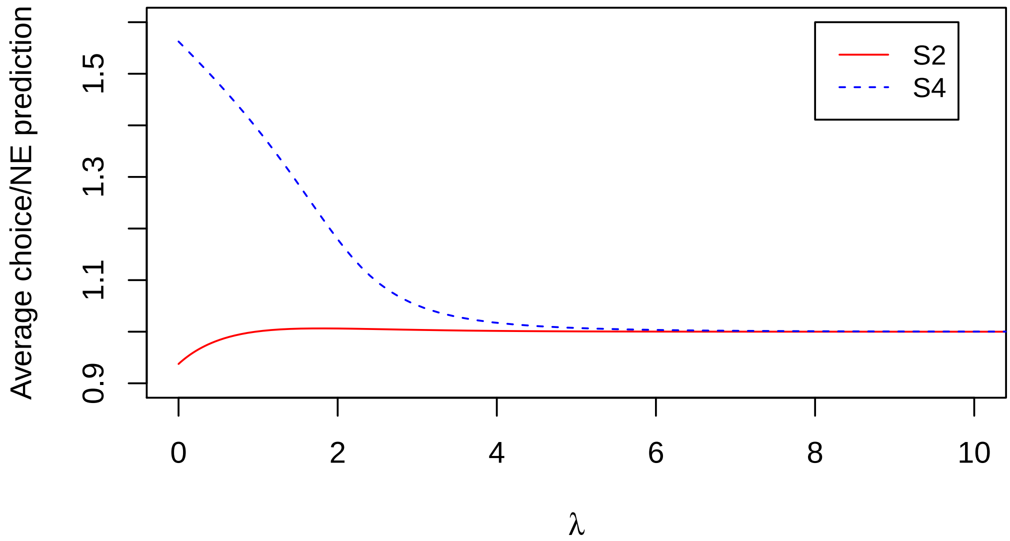
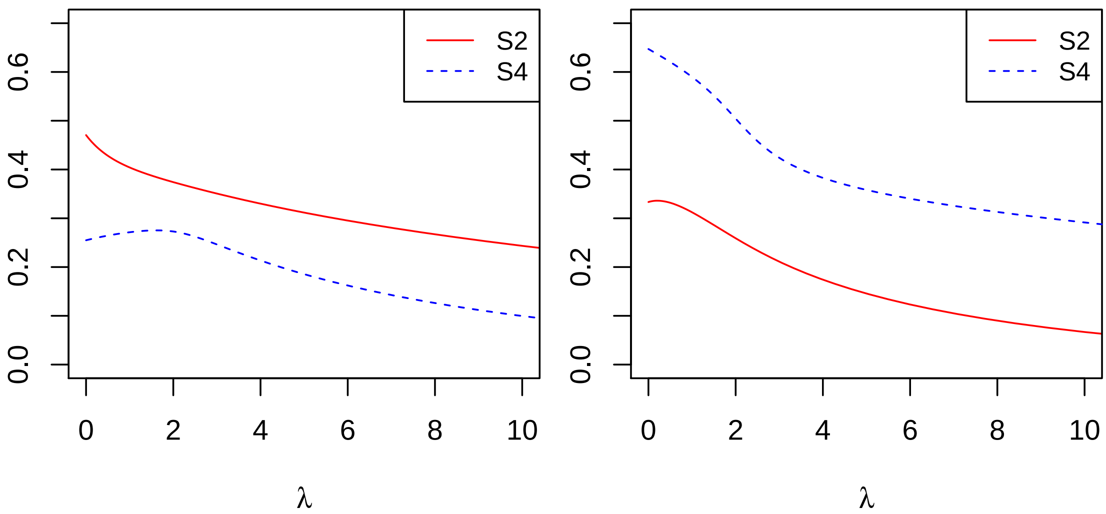


Figure 2: Ratio of average QRE output to Nash equilibrium output in standard treatments.



(a) Collusive output (b) Competitive output

Figure 3: Fraction of choices classified as collusive (closer to the collusive outcome than to the other two outcomes) or competitive (closer to the Walrasian equilibrium than to the other two outcomes) in standard treatments.

absolute difference from either the collusive outcome, Nash equilibrium or Walrasian equilibrium. We then calculate the relative frequency of choices in each category for each treatment. Figure 3 shows that QRE predicts a higher frequency of collusive output and a lower frequency of competitive output in the treatment with a smaller group size, for a wide range of λ values.

Overall, both measures indicate that when the group size is manipulated using the standard Cournot payoff function, QRE predicts more collusive behaviour in smaller groups. We conclude that the previously documented increased collusiveness in more concentrated markets could be driven by changes in incentives or locations of the key outcomes.

3.2 QRE in Normalized Treatments

Next, we study the QRE predictions in normalized treatments. The normalized payoff function was designed to keep the incentives similar across different group sizes, thus we expect that the group size will have little predicted effect on the collusiveness of output in the normalized treatments.

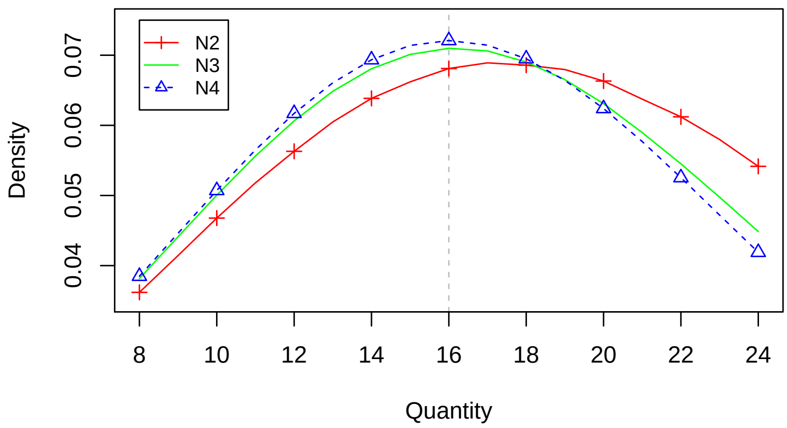


Figure 4: QRE distribution in normalized treatments at $\lambda = 1.5$. Vertical dashed line indicates Nash equilibrium output.

Figure 4 illustrates the QRE distribution for $\lambda = 1.5$. QRE distributions are similar in N3 and N4, but somewhat shifted towards more competitive output in N2. This shift is caused by the difference in the shape of the belief distribution. Holding the beliefs about any individual opponent constant, the distribution of beliefs about the average output would have a lower variance when the group size is large, because in such groups extreme values of average output are less likely. Higher variance of the belief distribution in N2 increases the attractiveness of higher output, because such output generates higher expected payoffs when the average output of the opponents is more extreme (see the payoffs in Table F.1, Appendix F).

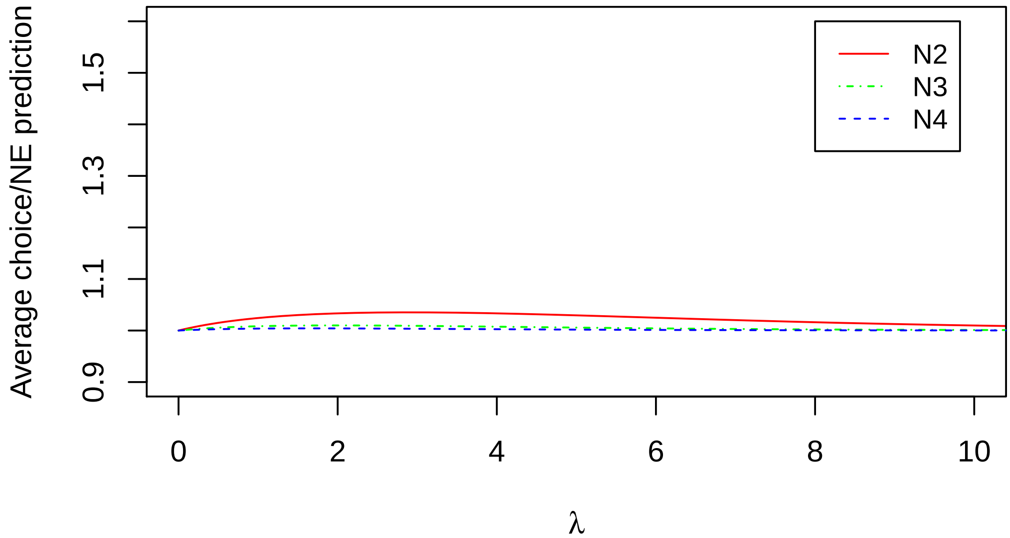
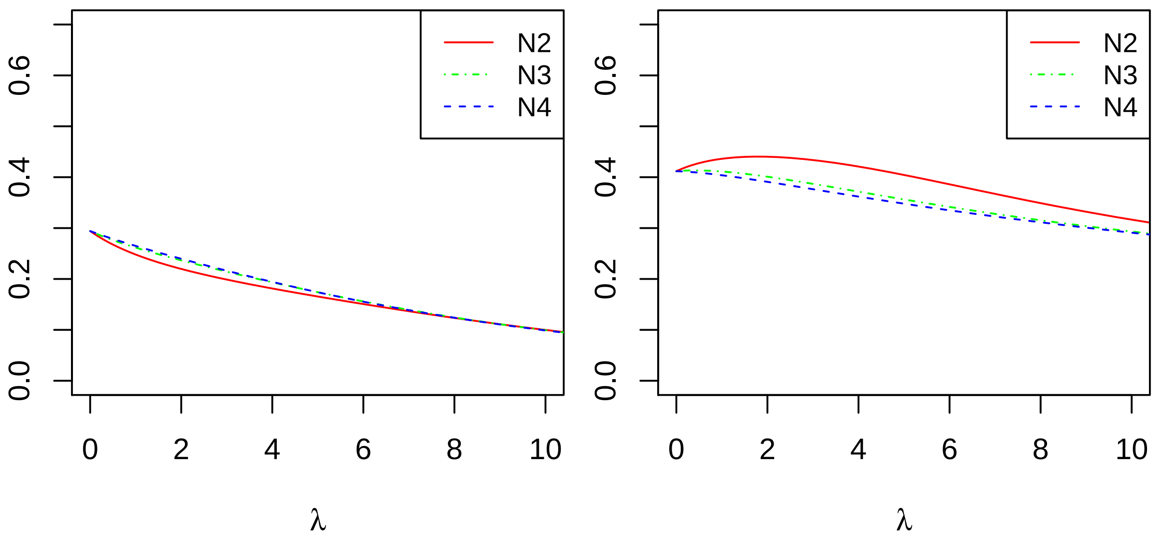


Figure 5: Ratio of average QRE output to Nash equilibrium output in normalized treatments.



(a) Collusive output

(b) Competitive output

Figure 6: Fraction of choices classified as collusive (closer to the collusive outcome than to the other two outcomes) or competitive (closer to the Walrasian equilibrium than to the other two outcomes) in normalized treatments.

We quantify collusiveness using the two measures introduced in the previous section: a ratio of average output to Nash equilibrium output and the frequency of output classified as either collusive or competitive. Figures 5 and 6 show the QRE predictions about these measures across a range of λ values. Figure 5 plots the ratio of average QRE output to Nash equilibrium output. In contrast to the standard treatments (Figure 2), we find that smaller groups are predicted to be slightly less collusive. However, the treatment difference is much smaller compared to the standard treatments: the ratio differs by at most 5%, in contrast to the differences of up to 60% in the standard treatments. Figure 6 shows that the slightly less collusive output in markets with two firms is primarily driven by a higher frequency of competitive choices in this treatment. The predicted fraction of collusive choices is nearly identical across the different group sizes, and much smaller than the differences in the standard treatments.

Overall, QRE predicts that smaller groups should be more collusive only in the standard but not in the normalized treatments. Comparing the group size effect in both designs can therefore identify whether the results found in the Cournot literature are primarily driven by the pure group size effect, or by the changes in incentives and salience.

4 Results

First, we compare the group size effect on aggregate output in the standard and normalized treatments. Afterwards, we compare the distributions of output and classify behavior to identify how the group size affects the frequency of collusive output.

4.1 Aggregate Output

In the standard treatments, theoretical predictions change with the group size, therefore average output ($\bar{q}_i$) needs to be normalized to compare the treatments. We do so using two measures of collusion: the ratio of actual to predicted output and a collusion index.

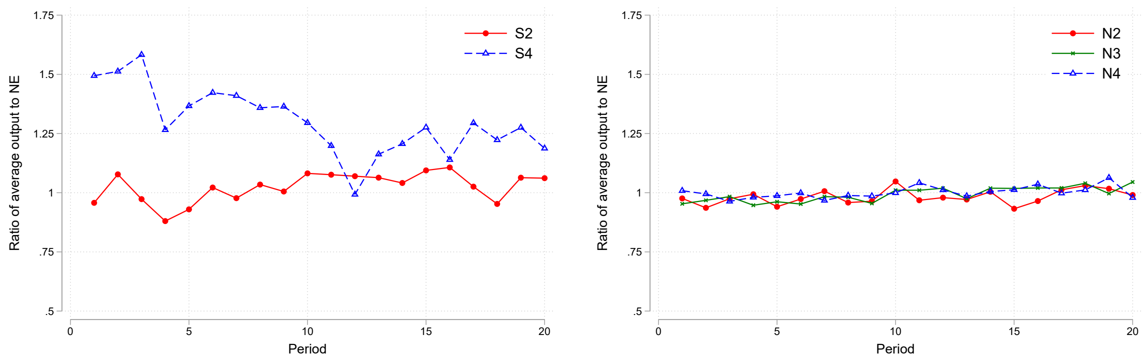


Figure 7: Ratio of average output to equilibrium output by treatment over time.

Table 2: Three measures of collusion and profits across treatments. The first number is the average in rounds 1-20; the number in brackets is the average in rounds 15-20.

Index	S2	S4	N2	N3	N4
r	1.02	1.30	0.98	0.99	1.00
	[1.05]	[1.23]	[0.99]	[1.02]	[1.02]
φ^N	-0.10	-0.80	0.05	0.02	-0.002
	[-0.20]	[-0.62]	[0.02]	[-0.06]	[-0.04]
φ^W	0.63	-0.08	0.43	0.41	0.40
	[0.60]	[0.03]	[0.41]	[0.36]	[0.37]
π_i	340.0	230.1	387.3	371.1	372.4
	[338.8]	[243.9]	[381.9]	[348.0]	[361.9]

Ratio of actual to predicted output. A common way to normalize output is to calculate the ratio of chosen output to Nash equilibrium output: $r = \bar{q}_i/q_i^N$. Values below (above) 1 indicate that output is more (less) collusive than the equilibrium prediction. Figure 7 shows the dynamics of the across-markets average r. We evaluate the statistical significance by calculating r separately for each group, aggregated either across all rounds (1-20) and only the last five rounds (15-20), following the convention in the literature (e.g. Huck et al., 2004). We compare the distributions of average normalized output using a non-parametric Mann-Whitney U test (MWU); all the reported p-values are two-tailed. In standard treatments, there is a significant difference between the markets with two and four firms (MWU $p < 0.0001$ in all rounds and $p = 0.001$ in the last 5 rounds). This result is consistent with the previous literature, which finds that smaller groups tend to be more collusive (Horstmann et al., 2018). In the normalized treatments, there is no difference between markets with two, three or four firms (for the pairwise comparisons, MWU $p \geqslant 0.5826$ in all rounds and $p \geqslant 0.3123$ in the last 5 rounds).

Collusion index. Used in Horstmann et al. (2018), Engel (2007) and Suetens and Potters (2007), the collusion index measures where the market output falls in the range between the collusive outcome and the Nash equilibrium or the Walrasian equilibrium: $\varphi^N = (\bar{q}_i - q_i^N)/(q_i^C - q_i^N)$ and $\varphi^W = (\bar{q}_i - q_i^W)/(q_i^C - q_i^W)$. Both indexes would be equal to 1 if the market output was equal to the collusive output; the first index would be equal to 0 if output was equal to the Nash equilibrium and the second would be equal to 0 if output was equal to the Walrasian equilibrium. Note that in the normalized treatments, the treatment comparison is identical for all three indexes because the key outcomes are invariant to group size. We find that in the standard treatments, two-firm markets are more collusive than four-firm markets, as measured by φ^N (MWU $p = 0.0001$ in all rounds, $p = 0.0103$ in the last 5 rounds) or by φ^W (MWU $p < 0.0001$ in all or only the last 5 rounds). In the normalized treatments, there is no difference between the markets with two, three or four firms (for the pairwise comparisons, MWU $p \geqslant 0.5786$ in all rounds and $p \geqslant 0.3123$ in the last 5 rounds).

Table 3: Random effects GLS regression. Standard errors are clustered on the group level.

	Standard			Normalized		
	DV: r	DV: φ^N	DV: φ^W	DV: r	DV: φ^N	DV: φ^W
3-firm market	-	-	-	0.0109	-0.0291	-0.0175
				(0.42)	(-0.42)	(-0.42)
4-firm market	0.277***	-0.705***	-0.716***	0.0189	-0.0504	-0.0303
	(6.37)	(-4.96)	(-11.02)	(1.04)	(-1.04)	(-1.04)
1/Round	0.206*	-0.501	-0.340**	-0.0382	0.102	0.0611
	(2.49)	(-1.96)	(-2.68)	(-1.75)	(1.75)	(1.75)
Decreasing labels				-0.0903***	0.241***	0.144***
				(-5.19)	(5.19)	(5.19)
Constant	0.988***	-0.00840	0.695***	1.034***	-0.0907	0.346***
	(32.33)	(-0.07)	(16.45)	(58.88)	(-1.94)	(12.30)
N	1920	1920	1920	5280	5280	5280

z statistics in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

From a policy perspective, it is important to know whether firms in more concentrated markets receive higher profits. Nash equilibrium predicts identical profits in all five treatments. Table 2 shows that in the standard treatments, profits are significantly higher in two-firm markets, both overall (MWU $p < 0.0001$) and in the last 5 rounds (MWU $p = 0.0001$). In contrast, the differences between the three normalized treatments are not significant (for all pairwise comparisons, MWU $p \geqslant 0.2323$ in all rounds and $p \geqslant 0.1450$ in the last 5 rounds).

Additionally, we evaluate the treatment effects using a panel data GLS regression with a random effect on the group level, taking into account the inter-temporal dependence of decisions as well as the dependence among the outputs of firms in the same group. Standard errors are clustered on the group level. As dependent variables, we use the three collusion indexes (r, φ^N, φ^W). We measure the group size effect by including dummy variables for each group size. For the normalized treatments, we also include an indicator of the strategy space labeling. A variable equal to the inverse of a round is included to capture changes in collusion due to experience. Table 3 shows that in the standard treatments, markets with four firms are significantly less collusive than markets with two firms, for all three indexes. The coefficients of the inverse round variable indicate increasing collusion over time. In the normalized treatments, the three-firm and four-firm markets are not different from the two-firm markets. The "decreasing labels" variable indicates treatments in which higher output was labeled with lower numbers. The positive estimated coefficient of this variable shows increased collusiveness when the strategy space is reversed; it is largely driven by the salience of producing 10 units, which is competitive with the increasing strategy space, but collusive in decreasing treatments. Note that in normalized treatments, strategy space labeling has a much stronger effect than the group size.[16]

These results are robust to different specifications. Table D.3 in Appendix D shows the estimated treatment effects using data only from the last 5 rounds, when participants would have accumulated experience. The treatment effects remain qualitatively the same. Results also do not change if we remove decisions that were implemented because participants failed to make a decision within the time limit. In the normalized treatments, we ran regressions separately for the decreasing and increasing strategy space and found no significant group size effect (Table D.2 in Appendix D). Including age and gender does not change the results, and coefficients for these two variables are not significantly different from zero.

Result 1. *In standard treatments, aggregate output is more collusive in markets with fewer firms. In normalized treatments, group size has no effect on aggregate output.*

4.2 Distribution of Output

So far, we have shown that group size does not change the average collusiveness of output when the payoff function is normalized. Studying the effect on average output and profits is important for policy, but we are also interested in how the group size changes the distribution of output, and particularly whether the frequency of collusive choices is higher in smaller groups.

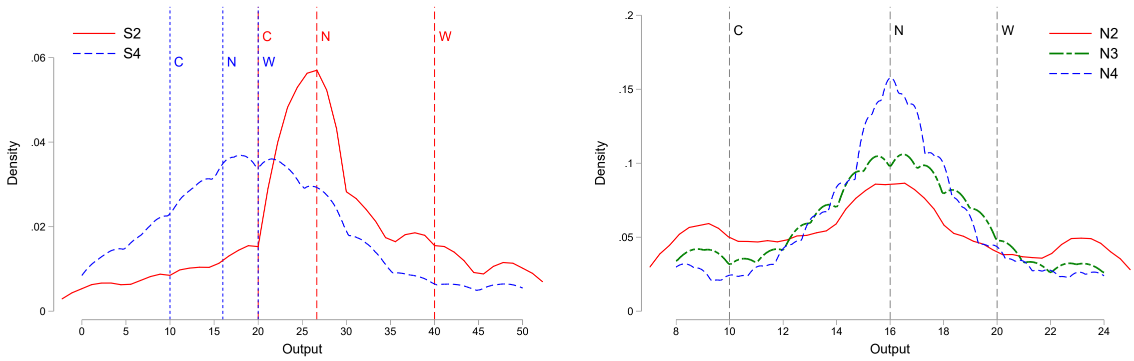


Figure 8: Kernel density estimation of individual output, pooled across rounds. We used Epanechnikov kernel function.

Figure 8 shows the kernel density estimation of individually chosen output. In standard treatments, average output is higher in smaller groups, but the treatment difference is not as strong as predicted by Nash equilibrium. Consequently, the average output is close to the equilibrium prediction in two-firm markets, but exceeds it in four-firm markets. In normalized treatments, output distributions are centered around the Nash

[16]The effect of strategy space labeling is discussed in more detail in Appendix A.

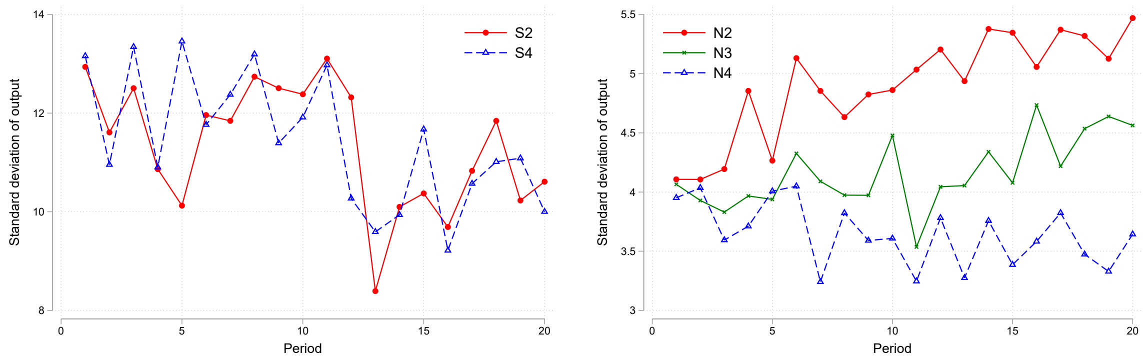


Figure 9: Standard deviation of output by treatment over time.

equilibrium but the variance is notably lower in markets with more firms: the standard deviation of chosen output is 4.9 in N2, 4.2 in N3 and 3.7 in N4. We evaluate the statistical significance of these differences by calculating the standard deviation of individually-chosen output in each group and comparing the difference between treatments. In normalized treatments, we find that the standard deviation is significantly higher in two-firm markets, compared to the markets with more firms (MWU $p = 0.0041$ comparing N2 to N3 and $p = 0.0017$ comparing N2 to N4). In standard treatments, group size has no significant effect on the standard deviation. Figure 9 plots the evolution if the standard deviation, calculated using all choices in each round. In standard treatments, there is no difference between the two group sizes. In normalized treatments, there are no treatment differences at the start of the game, but a gap between the three treatments appears and grows over time.

Differences in the choice distributions affect the fraction of choices classified as collusive. We use two methods to identify the frequency of collusion. First, we use collusion counts (Waichman et al., 2014), defined as the number of rounds in which quantities are in the collusive region, that is closer to the collusive outcome than to the Nash equilibrium. Unlike Waichman et al. (2014), we perform the classification using individual rather than total market output, because market output in large groups would fall into the collusive range only if the majority of firms act collusively, which is less likely than in smaller groups, thus underestimating the degree of collusion.[17] The average number of rounds in which individual output is classified as collusive is 5.1 in S4 and 5.2 in S2, a difference that is not significant (MWU $p = 0.49$). In normalized treatments, collusion counts go up from 3.0 in N4 to 4.1 in N3 and 5.8 in N2; there is significantly more collusion in two-firm markets than in three-firm markets (MWU $p = 0.0299$) or four-firm

[17]Classification using the market output replicates the usual finding of more collusive choices in smaller groups: in standard treatments, the average collusion counts go up from 5.1 to 10.3; in normalized treatments, from 3.7 to 8.1 to 9.0. The difference between the markets with two and four firms is significant in both standard (MWU $p = 0.0084$) and normalized treatments (MWU $p = 0.0009$). The three-firm market is not significantly different from the other two.

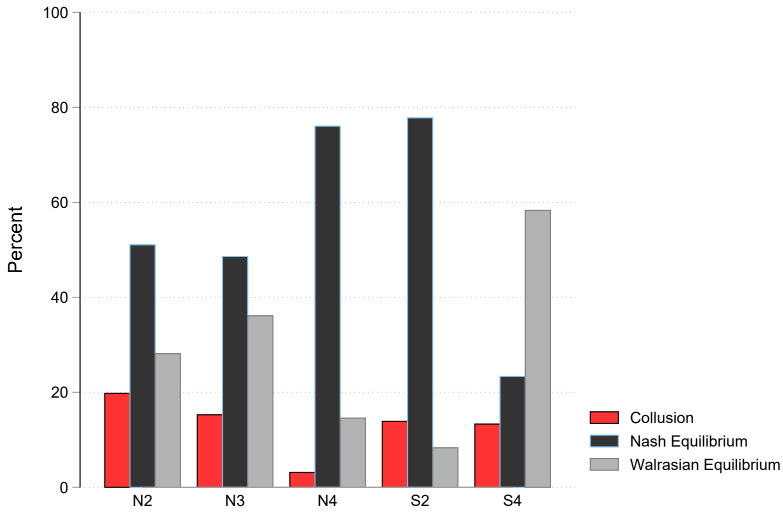


Figure 10: Classification of choices according to which outcome they are closest to. Data from the last 5 rounds.

markets (MWU $p = 0.0018$).

The comparison of collusion counts indicates a higher incidence of collusion in markets with fewer firms, in contrast to the results based on aggregate output. Figure 8 reveals that this result in normalized treatments is explained by smaller groups having a higher frequency of both collusive and competitive choices. We investigate these differences in more detail by classifying individual output based on the closest key outcome. We follow Huck et al. (2004), but use output from individual firms rather than the total market output. To identify whether output converges to one of the key outcomes, we use the average output of each firm in the last 5 rounds. Figure 10 shows that in standard treatments, a larger group size increases the fraction of choices classified as Walrasian but has no effect on the frequency of collusive choices. In normalized treatments, a larger group size decreases the frequency of collusive choices but has a non-monotonic effect on the frequency of Walrasian or Nash choices. Increased incidence of collusion in smaller groups might indicate that some of the small groups managed to implicitly collude; however, the next section will also show that it might instead reflect higher variance due to a change in feedback that participants receive.

Result 2. *In normalized treatments, the frequency of collusive output and the variance of output are higher in smaller groups. In standard treatments, group size has no effect on either of them.*

5 Model Estimation

Our standard treatments reproduce the results from the previous literature, finding that output is on average more collusive in smaller groups. In contrast, group size in the normalized treatments does not affect the aggregate output or profits, but smaller groups feature a higher variance of output, an effect that is not found in the standard treatments. This section will investigate how these data patterns can be explained.

5.1 Quantal Response Equilibrium

First, we test whether the data patterns can be explained by QRE. Section 3 has shown that QRE correctly predicts that a decrease in group size will increase collusiveness in the standard, but not in the normalized treatments. QRE also makes predictions about the entire distribution of choices, therefore we can test whether it can explain the change in the variance observed in the normalized treatments. Logit QRE is estimated using a method adapted from Bajari and Hortacsu (2005): we calculate the noisy best-response to the empirical choice distribution, and use a grid search procedure to find a precision parameter (λ) that maximizes the likelihood of producing the data observed in the experiment. This method provides an unbiased estimate of the precision parameter under the assumption that QRE is correct because in QRE beliefs would coincide with the empirical distribution. In practice, QRE will never fit the data perfectly, so there will be a discrepancy between this method and the tracing procedure we used to compute QRE in Section 3.[18]

When estimating QRE, we either fit a separate model for each treatment, or fit a single model, combining data from all five treatments. In the literature, it is common to estimate a separate model for each game (e.g. Lim et al., 2014), but this method implicitly assumes that the sensitivity to payoff differences is changing with group size. If very different values of λ are needed to explain the group size effect, results would be driven not by the elements in QRE, but by some other unmodeled factors. The second method therefore tests whether the differences between all treatment can be explained with a single value of the precision parameter.[19]

[18] There are two main benefits of using the estimation procedure from Bajari and Hortacsu (2005). First, it gives the flexibility to perform a combined estimation using multiple treatments with different payoff function, which is not possible with the standard tracing procedure. Second, the computational complexity of the estimation procedure is greatly reduced, since it is no longer necessary to compute the fixed point for a large number of parameter values. Computational complexity is especially problematic for the games with many participants and a large strategy space, such as our S4 treatment (51 strategies for each of the 4 participants).

[19] We also estimated QRE separately for normalized and standard treatments, requiring λ to be the same across different group sizes but allowing them to differ between standard and normalized treatments. This is justified by the important differences between standard and normalized treatments, such as the range of payoffs or the size of the strategy space, which affect the QRE predictions. In practice, the estimates are very close to the combined estimation. We report these results in Appendix D.

Table 4: Goodness of fit and estimated parameter values in QRE.

	Separate estimation		Combined estimation	
Treatment	$\hat{\lambda}$	LL	$\hat{\lambda}$	LL
S2	1.395	-2739.97	1.497	-2740.34
S4	1.535	-4561.56	1.497	-4561.65
N2	-0.292	-5436.98	1.497	-5531.25
N3	2.507	-4014.05	1.497	-4024.05
N4	4.686	-5161.69	1.497	-5281.54
Total		-21914.25		-22138.83

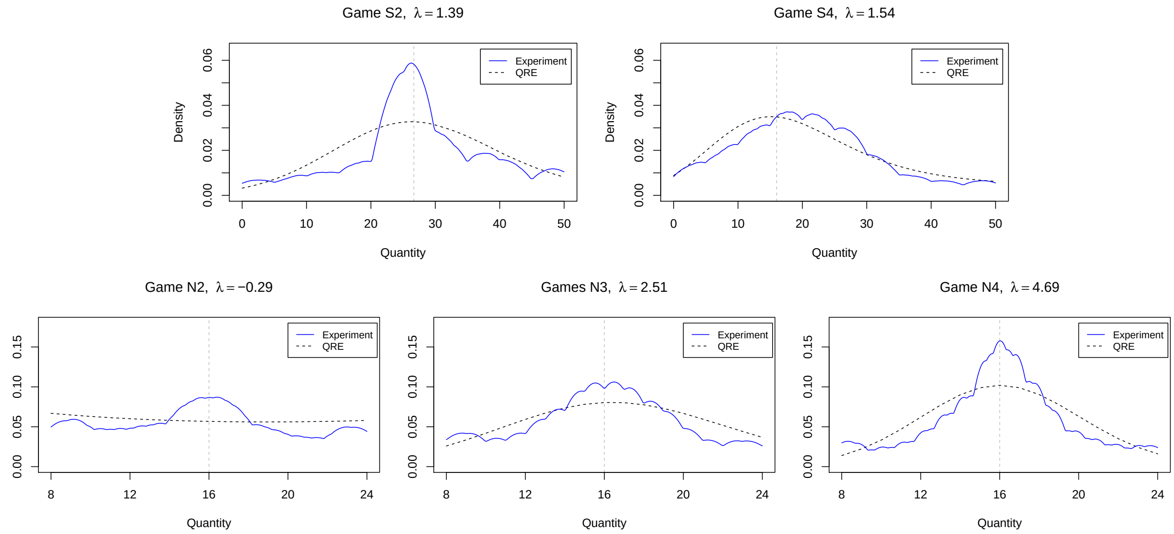


Figure 11: Best-fitting QRE, estimated separately for each treatment, compared to the kernel density estimation of the experimental data.

Table 4 provides an overview of the estimated parameter values and goodness of fit (log likelihood) for each method. When a separate model is fit for each game, the estimated values of the precision parameter are similar in the two standard treatments ($\hat{\lambda} = 1.4$ and $\hat{\lambda} = 1.5$), but very different in the three normalized treatments. Therefore, QRE can explain the group size effect in standard treatments (Result 1), but cannot explain the increased variance in smaller groups of the normalized treatments (Result 2), unless it is assumed that sensitivity to expected payoff differences is lower in markets with fewer firms. In fact, the estimated value of the precision parameter is negative in N2, indicating that the output distribution in this treatment could be explained by participants choosing actions with lower expected payoffs.

Figure 11 illustrates the goodness of fit by comparing the kernel density estimation of the experimental data to the choice probabilities predicted by the best-fitting QRE. In the standard treatments, QRE can explain the shift in the choice distribution driven by the group size. In the normalized treatments, the fit is less good as QRE underestimates the frequency of salient outcomes, such as the Nash equilibrium and the endpoints of the strategy space, even when a separate model is fit for each treatments. The additional

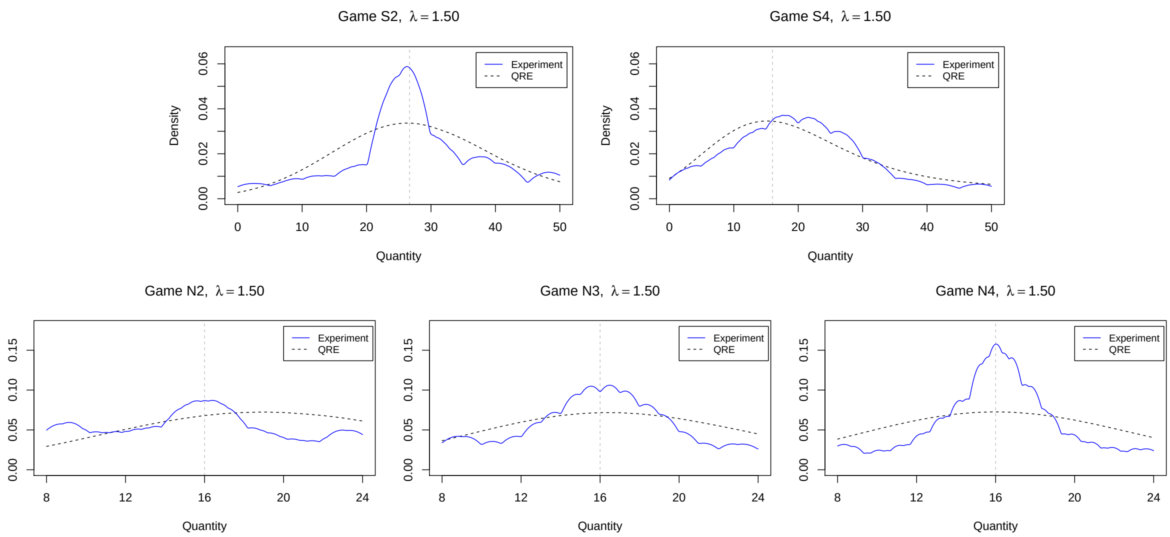


Figure 12: Best-fitting QRE, estimated for all treatments, compared to the kernel density estimation of the experimental data).

requirement for the precision parameter to be constant across treatments in the second method hardly changes the fit in the standard treatments, but decreases the fit in the normalized treatments, especially in N2 and N4. Figure 12 shows the choice probabilities in the best-fitting QRE with a single value of $\hat{\lambda} = 1.497$. The model with a single parameter value can explain the change of the output distribution in the standard treatments, but not in the normalized ones.

Overall, QRE can explain why output is on aggregate more collusive in smaller groups in standard treatments and why there is no difference in the normalized treatments (Result 1). QRE can also explain the overall change in the shape of the choice distribution in standard treatments, but it cannot explain why variance decreases in group size in the normalized treatments (Result 2).

5.2 Best-response Likelihood

We propose that the increased variance of output in smaller groups of the normalized treatment could be explained by the increased likelihood that extreme output values will maximize payoffs. In the normalized treatments, payoffs and the best response depend on the *average* output of the opponents; in standard treatments, they depend on the *sum* of output. The difference is important because an increase in the number of opponents reduces the variance of the mean, but increases the variance of the sum. A higher variance in the payoff-relevant statistic translates into a higher variance of the best-response distribution, as it becomes more likely that extreme output values will maximize ex-post payoffs.

Figure 13 illustrates this effect in the normalized treatments. We model the best-response distribution of a player who expects all opponents to independently draw their

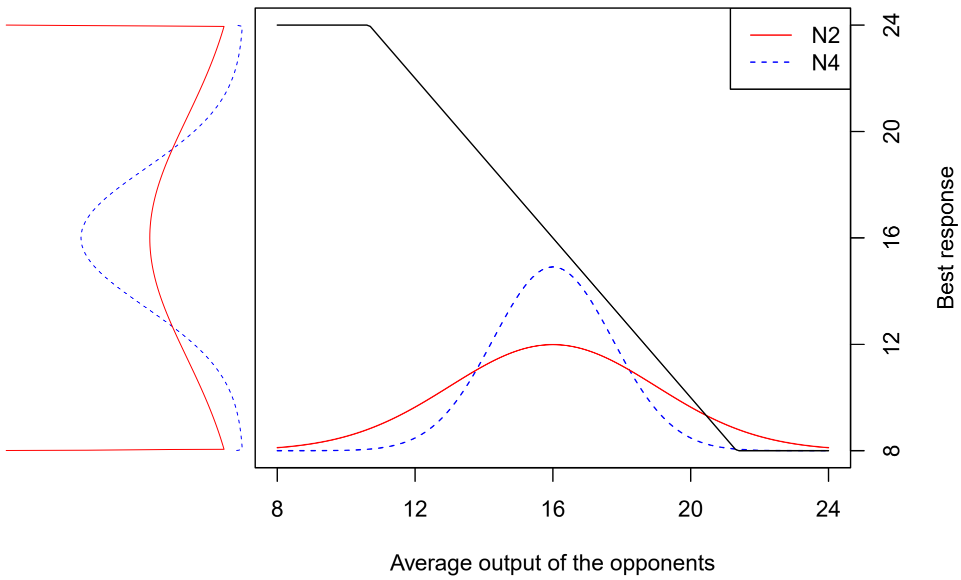


Figure 13: Best-response curve, probability distribution of average output of the opponents and the resulting probability distribution of the best response (on the left). Standard deviation is set to 3.

output from a normal distribution (or opponents are randomly sampled from a population). The red line in Figure 13 illustrates the distribution of average output expected by the players who face a single opponent. The blue dashed line illustrates the distribution expected by players who face three opponents. The variance of the latter is lower because the average of three independent draws is less likely to differ from the population mean than a single draw. The black kinked line shows the best-response correspondence, which maps the distribution of average output into the best-response distribution, plotted on the left. The best-response function translates higher variance of the average opponents' output into higher variance of the best-response distribution. We therefore predict that when payoffs depend on mean output, players in smaller groups would more often observe extreme values and would best-respond by more frequently choosing extreme output values. Note that this prediction does not hold in the standard treatments, where choices are aggregated by taking the sum, because the sampling distribution of the sum has a higher variance when the sample is larger. The exact predictions about the variance in standard treatments depend on the assumed parameter values, as summing changes both the variance and the mean of the payoff-relevant statistic (for more details, see Appendix C).

In the experiment, this mechanism implies that in small groups of the normalized treatment, participants would experience higher variance of the average output chosen by the opponents, and would therefore more often find that extreme output values are the best response. We can test this prediction by comparing the incentives to respond to the observed feedback. First, we test the prediction that the variance of total output of the opponents is increasing in group size, but the variance of average output is decreasing. For each participant, we calculate the standard deviation of either the total or the mean

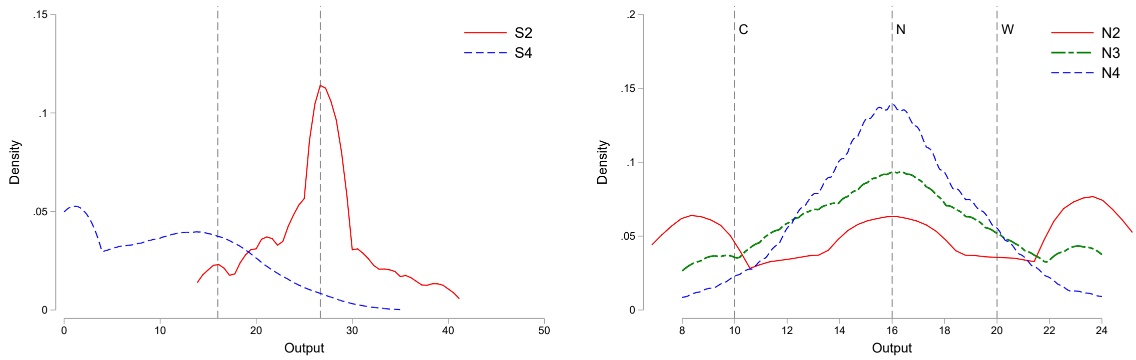


Figure 14: Kernel density estimation of ex-post rational actions, pooled across all rounds.

opponents' output across all 20 rounds and then compute the standard deviation in each treatment. As predicted, the standard deviation of the total opponents' output increases from 10 in S2 to 19 in S4 in standard treatments. In normalized treatments, the standard deviation of the average opponents' output decreases from 4.2 in N2 to 2.3 in N3 and 1.9 in N4.

These differences affect the shape of the best-response distribution. Figure 14 shows the distribution of Cournot best-replies to the output of the opponents, aggregated across all participants and all rounds. These distributions would be observed if participants expected the opponents to make the same choices as in the previous round, and best-responded to those beliefs. Standard deviation of the best-response distribution is increasing in group size in the standard treatments (5.7 in S2 and 8.1 in S4) but decreasing in the normalized treatments (5.8 in N2, 4.4 in N3 and 3.1 in N4). This result shows that the observation of variance decreasing in group size only in the normalized treatments could be explained by participants responding to observed feedback.

So far, we have shown that the difference in choice aggregation could change the feedback that participants typically observe, thus altering the choices of those who myopically best-respond to such feedback. This explanation is consistent with the experimental data, but we have not yet discussed a formal model that could explain such behavior. We propose such a model, which we call Frequent Response Equilibrium (FRE), in Appendix C. FRE is an modification of QRE, based on the concept that the probability to choose an action depends on the likelihood that the action is the best response, instead of the expected payoff that the action generates, as is assumed in QRE.[20] QRE could emerge as

[20]The action that generates the highest expected payoff is different from the action that is most likely to provide the highest payoff, because the former does not take into account the magnitude of payoffs. For example, consider our N2 treatment and suppose that players expect the opponent to draw their action from a uniform distribution. Compare the equilibrium output of 16 to the lowest possible output of 8. Producing 16 provides a higher expected payoff than 8 because it generates high profits when the opponent is choosing a low or an intermediate output level (Table F.1). However, 16 is rarely the exact best-response – it is the best response only if the other player chooses 16 as well, whereas 8 is the best response to any output above 21. When evaluated based on the likelihood to be the best response, output of 8 would therefore outperform 16, while 16 would outperform 8 based on the expected payoff.

the long-run outcome of logit response dynamics (Alós-Ferrer and Netzer, 2010; Cason et al., 2021), as players form beliefs from observed history and choose stochastic best-responses. Instead, FRE could emerge as the long-run outcome if players favor actions that are frequent best-responses to the observed history, in a manner similar to probability matching (Vulkan, 2000). FRE assumptions are also in line with the empirical evidence: when decisions are made from experience, many participants choose the action that is usually the best-response, rather than the action that generates highest expected payoffs (Erev and Barron, 2005; Yechiam and Busemeyer, 2006).

When we fit FRE to the data and compare the goodness of fit to QRE, we find that it has a better overall fit, and performs worse than QRE only in the S4 treatment, where it overestimates the frequency of extreme output levels (Table C.1 in Appendix C). The better fit is quite remarkable since FRE uses much less information about the game structure – only whether the action is the best response, ignoring the magnitude of payoff differences. A hybrid model that takes into account both the likelihood to be the best response and the magnitude of payoffs would likely further improve the fit and could be used to understand patterns in other games. Overall, we conclude that the increased variance in smaller groups, found in the normalized treatments, can be explained by a static solution concept based on the likelihood that an action is the best response.

6 Concluding Remarks

Previous Cournot oligopoly experiments found higher rates of tacit collusion in smaller groups. We demonstrate that this result could be explained by changes in the payoff structure that occur when the group size is manipulated using the standard Cournot payoff function. We propose an alternative way to manipulate the group size, which makes markets with a different number of competitors more comparable. This normalized design is used to identify whether differences in collusion rates are driven by the group size itself, or by the changes in incentives or the salience of key outcomes. We replicate the finding of more collusive output in smaller groups using the standard design, but find no effect of group size in the normalized treatments. These results suggest that the group size effect is largely driven by the changes in incentives or salience, instead of purely the number of interacting firms.

In the normalized treatments, we also find that the variance of individual output is decreasing in group size. This effect cannot be explained by the Quantal Response Equilibrium. Instead, it could be explained by the difference in feedback caused by the implemented aggregation rule: total output in standard treatments, average output in normalized treatments. The variance of average output decreases in larger groups, making extreme output values rarely the best-response. Instead, the variance of total output increases in larger groups. Interestingly, increased variance in smaller groups in the normalized treatments provides some support for the original result of higher frequency of collusion in smaller groups, although the frequency of competitive choices goes up as well.

A better understanding of how the number of competitors affects collusion rates could improve the design of competition policy. When deciding whether to approve a merger, regulators evaluate whether the resulting increase in market concentration would significantly lessen competition. The practices used by the Department of Justice and the Federal Trade Commission, two agencies in charge of enforcing antitrust law in the U.S., are explained in the Horizontal Merger Guidelines.[21] The guidelines identify two channels through which mergers could enhance market power: "unilateral effects" and "coordinated effects".[22] Unilateral effects refer to the higher incentives to increase prices in more concentrated markets; for example, a merger of firms that sell similar products increases the incentive to raise prices because the lost sales that would have been diverted to the competitor's products are now diverted to the products sold by other divisions of the same firm. Coordinated effects refer to the increased likelihood of implicit or explicit coordination on higher prices in more concentrated markets. Successful coordination requires the ability to detect and punish the firms that deviate from collusive agreements,[23] which is easier when there are fewer firms and the behavior of rivals is more predictable. These two channels correspond to the two mechanisms studied in this paper: individual incentives and the pure group size effect. Just as the real firms, participants in Cournot oligopoly could collude more in smaller groups because of higher incentives or because implicit coordination is easier when there are fewer participants. Identifying the mechanism is critical to select the appropriate strategy for regulating mergers. If collusion is driven primarily by coordinated effects, regulators should focus on market concentration, as was advocated in the 1968 and 1982 guidelines (Shapiro, 2010). However, if it is primarily driven by the unilateral effects, regulators should instead estimate the value of diverted sales by evaluating the degree of product differentiation, market elasticity of demand or costs of output suppression. Recent versions of the guidelines advocate this view, introducing the concept of unilateral effects in the 1992 guidelines and accentuating it in 2010 (Shapiro, 2010). Consequently, the guidelines have focused more on the economic factors and techniques to estimate the value of diverted sales rather than the market concentration.[24] The results of our experiments support this shift, providing

[21]U.S. Department of Justice & Federal Trade Commission, Horizontal Merger Guidelines (2010), available at http://www.justice.gov/atr/public/guidelines/hmg-2010.pdf

[22]The European Commission provides similar guidelines, naming the two channels "coordinated effects" and "non-coordinated effects", see Guidelines on the Assessment of Horizontal Mergers under the Council Regulation on the Control of Concentrations between Undertakings, 2004 O.J. (L 24) 1 (EC), available at http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:C:2004:031:0005:0018:EN:PDF

[23]U.S. Department of Justice & Federal Trade Commission, Commentary on the Horizontal Merger Guidelines (2006), available at http://www.justice.gov/atr/public/guidelines/215247.pdf

[24]Section 4 of the 2010 Guidelines: "The measurement of market shares and market concentration is

evidence that collusion in concentrated markets occurs not because of a smaller number of competitors, but because of the increased incentives to collude. Mergers that do not create additional incentives to collude (e.g. in markets with a low diversion ratio and low margins, Farrell and Shapiro, 2010) might not need to be blocked even if they increase market concentration.

Our study also improves the understanding of the mechanism behind the group size effect, a question that is receiving more interest due to the possibility to study groups with hundreds or even thousands of interacting participants (Pereda et al., 2019; Choi et al., 2020; Li et al., 2021; Arifovic et al., 2022). In typical games, player's payoffs and the best-response depend on the mean, sum or the minimum choice of others. We show that the choice of measure, typically dictated by convention or external validity, has important consequences on how behavior is predicted to change with group size. When payoffs depend on the minimum choice, such as in the minimum effort game or Bertrand oligopoly with homogenous products, the risk of at least one participant selecting a low value is higher in larger groups. Therefore, in larger groups, players would receive higher expected payoffs from choosing lower numbers, as predicted by QRE. This mechanism has been identified in theoretical work (see Anderson et al., 2001 for the minimum effort game; see Baye and Morgan, 2004, and Bayer et al., 2019, for Bertand oligopoly) and it is consistent with experimental evidence (Van Huyck et al., 1990; Dufwenberg and Gneezy, 2000). However, the mechanism only works if payoffs depend on the minimum choice. Our study is the first to study the group size effect in the same game using two different aggregation rules: the mean and the sum. We show that when payoffs depend on total output, the group size affects the locations of key outcomes and the incentives to deviate from them; therefore, QRE predicts more competitive output in larger groups. In contrast, when payoffs depend on the average output, the expected payoffs remain similar across different group sizes and QRE predicts similar behavioral patterns. However, even though the differences between actions in terms of expected payoffs remain similar, the distribution of payoffs changes. In large groups, the variance of average output of other players is low, therefore extreme output values are rarely the best, but they are also unlikely to generate very low payoffs. In small groups, average output of others is much noisier, therefore extreme output is much more likely to be the best response, although it is also likely to generate very low payoffs. This difference can be critical if boundedly rational players choose the actions that are usually the best responses, instead of choosing based on expected payoffs. Future research on group size effects should therefore carefully study the potential mechanisms: incentives, labeling of strategies and the difficulty of coordination. Some of these mechanisms can be controlled, as we exemplified by creating the normalized treatments, while others can be accounted for by modeling boundedly rational behavior and comparing it to empirical data.

not an end in itself, but is useful to the extent it illuminates the merger's likely competitive effects".

The results presented here and the methods of studying the changes in incentives and feedback could pave the way for future research that would systematically study how the features of the game, such as the shape of the best-response function and aggregation rule, affect the incentives and feedback and therefore the changes in behavior in response to group size. The goal would be to understand why group size effects are found in some settings but not in others (e.g. see Arifovic et al., 2022 for a discussion about potential explanations in different coordination games). If the feedback-based explanation is correct, the results from the Cournot oligopoly might not transfer to other games due to the different shape of the best-response function. For example, in rent-seeking contest, the best-response function is hump-shaped, therefore greater variance in the payoff-relevant measure is predicted to increase the frequency of low effort, in contrast to the results in our normalized treatments, where it leads to a greater frequency of both very low and very high output. This hypothesis could be tested by manipulating the group size in contests, while keeping the payoffs invariant to the average, rather than total effort of others. Previous research, which used the latter aggregation rule, found just the opposite results, revealing higher frequency of low effort in large groups (Lim et al., 2014). It would be interesting to test if this effect would decrease or be reversed if payoffs depended on the mean rather than the total effort of others. More broadly, to understand the nature of the group size effect, it would be very interesting to study it under various combinations of aggregation rules and types of best-response functions.

Our study has several limitations that would be interesting to address in future research. We focused only on implicit collusion, but it would be interesting to compare our results to a framework in which explicit collusion is possible, perhaps by adding communication. On one hand, communication might increase the importance of coordination, preventing collusion in large groups; on the other hand, evidence shows that communication allows even large groups to collude, therefore the group size effect is not found even with the standard Cournot payoff function (Waichman et al., 2014; Fonseca et al., 2018). It would also be interesting to extend the setup to other games, such as a rent-seeking contest or Bertrand competition, where a similar groups size effect has been observed for both tacit and explicit collusion (Fonseca and Normann, 2012).

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Appendix

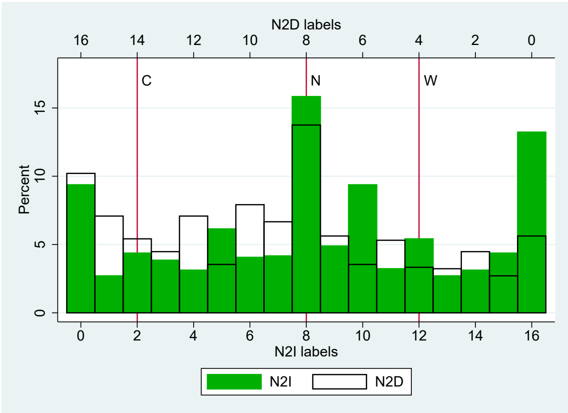
A Strategy Space Labeling in Normalized treatments

Table A.1: Comparison of the ratio of average output to NE prediction and average profit per round. The number in brackets shows the values averaged across rounds 15-20.

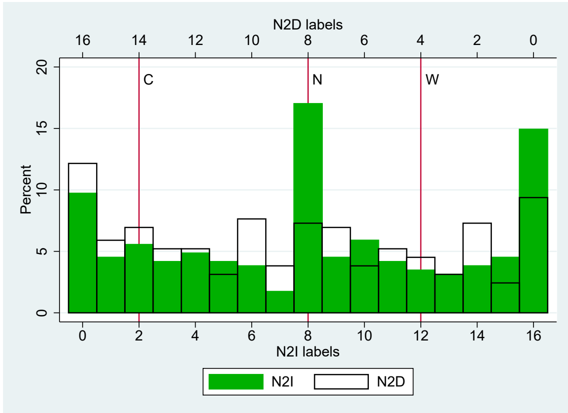
	N2I	N3I	N4I	N2D	N3D	N4D
q_i/q_i^N	1.03	1.07	1.03	0.94	0.92	0.98
	[1.02]	[1.10]	[1.02]	[0.97]	[0.95]	[1.02]
π_i	366.4	322.8	354.2	408.3	419.5	390.6
	[377.5]	[299.5]	[363.4]	[386.3]	[396.6]	[360.3]

The normalized treatments were run with one of the two labeling schemes. In both schemes, actions were labeled from 0 to 16, but in the "increasing" scheme, higher numbers represented higher output (i.e. 0 represented the output of 8, and 16 represented the output of 24), while in the "decreasing" scheme, the strategy space was reversed (0 represented the output of 24, and 16 represented the output of 8). First, we study the importance of labeling by comparing the ratio of average output to Nash equilibrium prediction across the two schemes, in each treatment. Table A.1 shows that on average, the chosen output is above NE prediction in increasing treatments, but below it in decreasing treatments. Mann-Whitney U test shows that in each treatment, output is significantly more collusive when the decreasing labeling scheme is used (MWU $p = 0.0111$ in four-firm treatments, $p = 0.0085$ in three-firm treatments and $p = 0.0296$ in two-firm treatments). We also test whether the effect of labeling persists over time, as it is commonly found that the framing effects are stronger at the start of the game Masiliūnas and Nax (2020). If we compare the average ratio of output to NE prediction in two schemes only in the last 5 rounds (see the numbers in brackets in Table A.1), we find that labeling effect remains significant only in the three-firm markets ($p = 0.0178$). A similar result is found in terms of the generated profits, which are significantly higher in the decreasing scheme when all data is used (MWU $p = 0.0153$ in four-firm treatments, $p = 0.0056$ in three-firm treatments and $p = 0.0392$ in two-firm treatments). In the last 5 rounds, the difference is significant only in three-firm treatments (MWU $p = 0.0243$). However, if we run a GLS regression using pooled data from all the normalized treatments, we still find more collusive output in the decreasing scheme ($p = 0.016$, Table D.3 in Appendix D), even though the effect is not as strong as when data from all rounds is used ($p < 0.001$, Table 3). We conclude that strategy space labeling has a consistent effect on collusiveness at the start of the experiment, although it vanes over time.

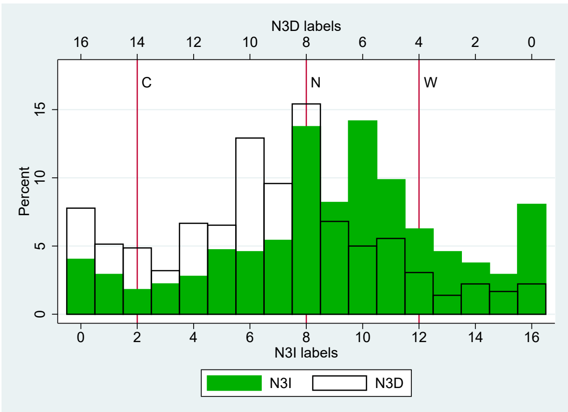
To understand why labeling affects output, we compare the distributions of choices in the two schemes. Figure A.1 overlays the histogram of output in the decreasing scheme (white) with the increasing scheme (green), indicating the labels seen by the participants



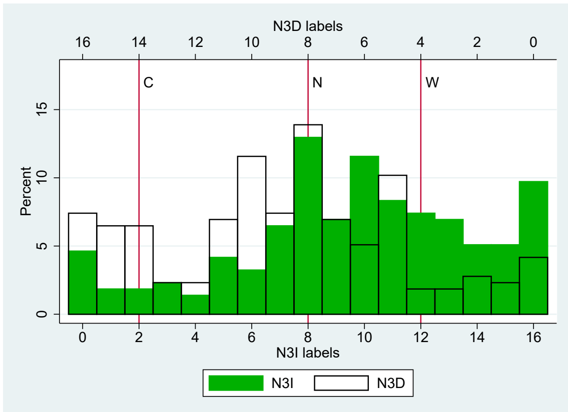
(a) N2, rounds 1-20



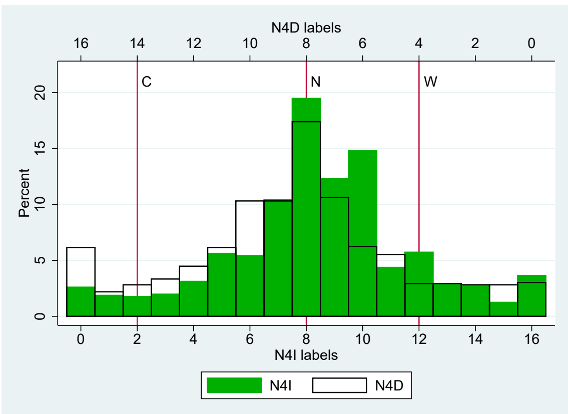
(b) N2, rounds 15-20



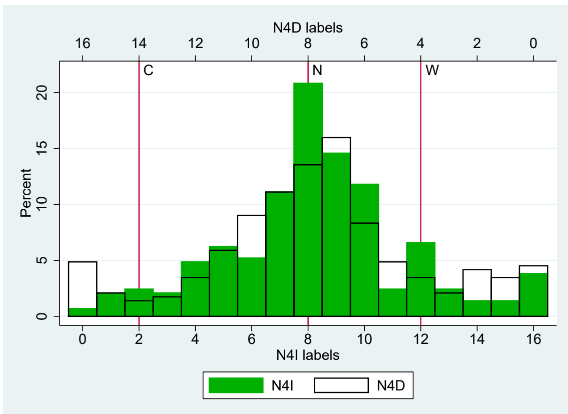
(c) N3, rounds 1-20



(d) N3, rounds 15-20



(e) N4, rounds 1-20



(f) N4, rounds 15-20

Figure A.1: Output distributions in normalized treatments for the increasing and deceasing labeling schemes. Vertical lines indicate the three key outcomes (collusive outcome, Nash equilibrium and Walrasian equilibrium).

on separate axes. Figures on the right plot data from all rounds. Data shows that choices tend to be more collusive in the decreasing scheme, in all three treatments. In part, the difference can be explained by action labeled as "10" being more salient and thus frequently chosen than the same action when it is labeled as "6". In the increasing scheme, the action labeled as "10" is midway between the Nash and Walrasian equilibria, but in the decreasing scheme, it is more collusive than the Nash equilibrium output. However, there are other differences as well. With all three group sizes, action 16 is chosen more often than action 0, regardless of whether it is mapped into output 8 or 24. There is also some evidence that the distribution of choices is shifted towards actions with higher labels, especially in the three-firm treatment. Thus it seems that the effect of labeling is driven both by the salience of action "10" and by a preference for choosing actions labeled with higher numbers. The right column of Figure A.1 shows the distribution of choices only in the last 5 rounds. The effect of labeling persists in markets with two and three firms, although the magnitude of the effect is lower.

The manipulation of the labeling scheme allows us to more accurately assess the aggregate collusiveness of output. Had we used only the increasing scheme, as was done in all the previous literature, we would likely conclude that there is a tendency to behave more competitively than predicted by the Nash equilibrium (see Table A.1). But the comparison to the decreasing scheme reveals that this tendency is driven in part by the labeling rather than the incentive scheme. By combining the data from two different labeling schemes, we can evaluate and eliminate the effect of such strategy space labeling.

B Response to Feedback

In this Appendix, we provide more details about how the difference in the output aggregation between the standard and normalized treatments changes the feedback that participants observe and thus the choices of those who follow Cournot best-response. In the standard treatments, the *sum* of opponents' output is mapped into the same best-response, regardless of the group size. In the normalized treatments, the *average* of opponents' output is mapped into the same best-response, regardless of the group size. The distribution of the total and average output varies with the group size, affecting the variance of the best-response distribution. As an illustration, suppose that each opponent chooses their output q_i from a normal distribution $\mathcal{N}(\mu, \sigma^2)$. Then the sum of the total output chosen by $(n-1)$ opponents is the sum of $(n-1)$ random variables drawn from the normal distribution.

Total output of the opponents thus follows the normal distribution with the following parameter values:

$$\sum_{j=1}^{n-1} q_j \sim \mathcal{N}((n-1)\mu, (n-1)\sigma^2)$$

Average output chosen by the $(n-1)$ opponents also follows the normal distribution:

$$\frac{1}{n-1}\sum_{j=1}^{n-1} q_j \sim \mathcal{N}(\mu, \frac{1}{n-1}\sigma^2)$$

Note that as the group size (n) increases, the variance of the total output goes up, but the variance of the average output goes down. This difference is subsequently translated into a difference in the variance of the best-response distribution, as illustrated in Figures B.1 and B.2. The curves inside the figures display the probability distributions of the payoff-relevant statistics – total output for standard treatments and average output for normalized treatments. The distributions are plotted assuming that the mean of the distribution is equal to the Nash equilibrium and the standard deviation is equal to 8 in standard and 3 in normalized treatments (close to the standard deviations seen in experiments, as shown in Figure 9). The variance of the total opponents' output is increasing in group size (Figure B.1), but the variance of the mean output is decreasing in group size (Figure B.2). The black line in each figure shows how the total or mean output chosen by opponents (which is on the x-axis) is mapped into the best response. The curves on the left side of the figure show the resulting distribution of best-responses to the corresponding distribution of either the sum or the mean output of the opponents. As one can observe, a higher variance of the latter distribution translates into a higher variance of the best-response distribution. We conclude that the variance of the best-response distribution would be predicted to increase in group size in standard treatments, but decrease in group size in normalized treatments.

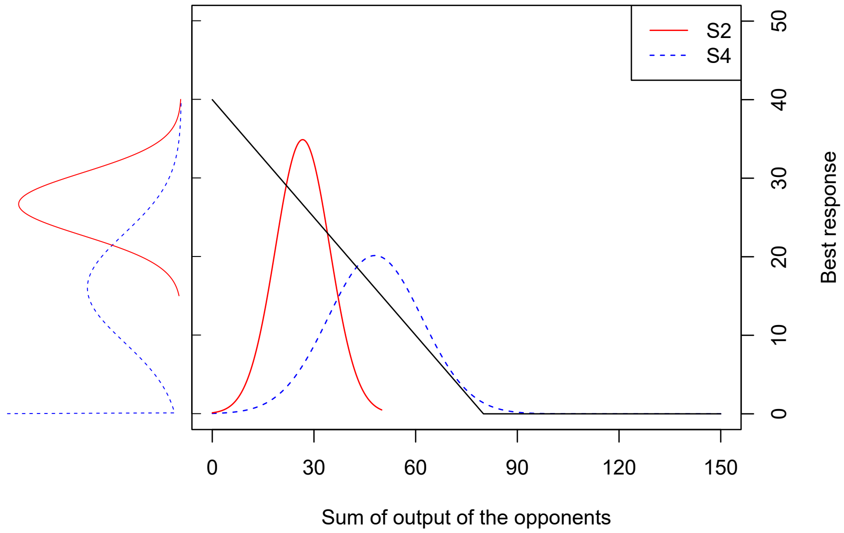


Figure B.1: Best-response curve, probability distribution of total output of the opponents and the resulting probability distribution of the best response (on the left). Standard deviation is set to 8.

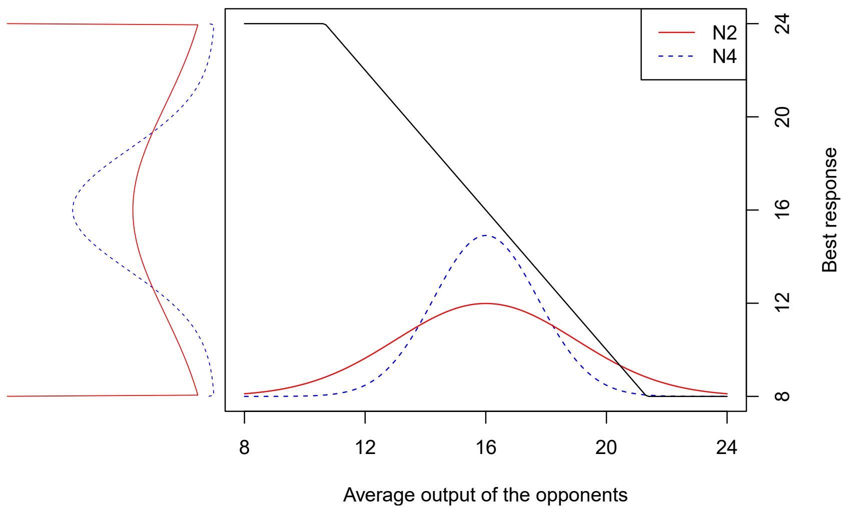


Figure B.2: Best-response curve, probability distribution of average output of the opponents and the resulting probability distribution of the best response (on the left). Standard deviation is set to 3.

C Frequent Response Equilibrium

This appendix formally defines the Frequent Response Equilibrium (FRE), which is an extension of QRE, presented in Section 3. We also fit FRE to the experimental data and compare the goodness of fit to QRE.

Let $q_{-i} = \{q_1, \ldots, q_{i-1}, q_{i+1}, \ldots, q_n\}$ be the pure strategy profile of all players other than i. Then $p_{-i} \in \Delta_{-i}$ is the mixed strategy profile of all others players, where Δ_{-i} is the the set of all possible mixed strategy profiles. The likelihood that q_{-i} will be played in p_{-i} is $p_{-i}(q_{-i})$. Denote the set of strategies that are best responses to a pure strategy profile q_{-i} by $B(q_{-i}) = \{q_k \in Q_i | \forall q_j \in Q_i : \pi_i(q_k, q_{-i}) \geqslant \pi_i(q_j, q_{-i})\}$. Then the likelihood that q_k is the best-response to q_{-i} is calculated by $b(q_k, q_{-i})$, defined as:

$$b(q_k, q_{-i}) = \begin{cases} \frac{1}{|B(q_{-i})|} & \text{if } q_k \in B(q_{-i}) \\ 0 & \text{if } q_k \notin B(q_{-i}) \end{cases}$$

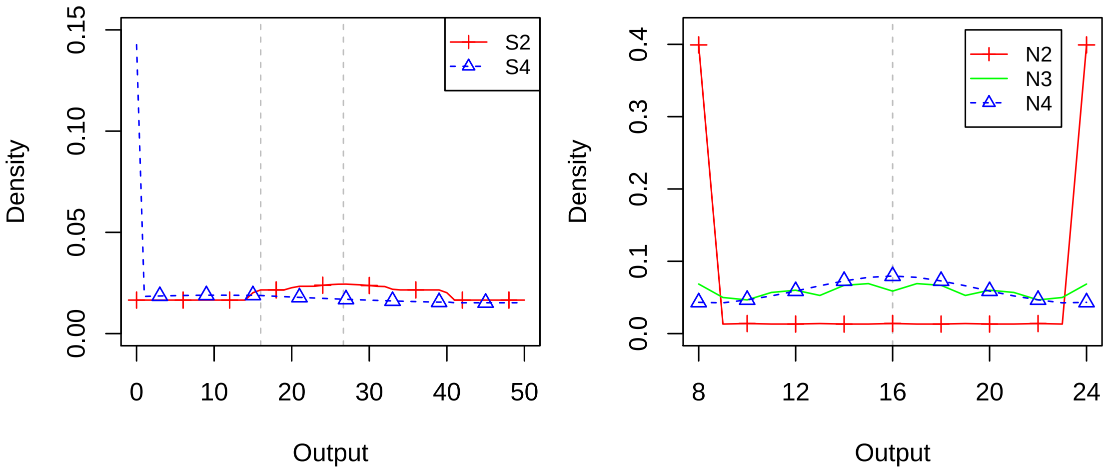
The likelihood that action q_k is the best-response conditional on probabilistic belief p_{-i} is calculated by $r(q_k, p_{-i}) = \sum_{q_{-i}} b(q_k, q_{-i}) p_{-i}(q_{-i})$. FRE assumes that player are maximizing the probability that the action will be the best response; therefore, the utility function defined in equation (2) is replaced by:

$$u_i(q_k, p_{-i}) = r(q_k, p_{-i}) + \varepsilon_{ik} \tag{4}$$

The definition of the solution concept follows the one of QRE, detailed in Section 3, with the choice probabilities determined by equation (3). We set up FRE to differ from QRE only in the way the attractions are determined (based on the likelihood of being a best-response rather than expected payoff), therefore we retained the assumption that attractions are mapped into choice probabilities using a softmax function with a λ parameter. If $\lambda \rightarrow \infty$, FRE approaches Nash equilibrium because the action that has the highest likelihood to be the best response must also provide the highest expected payoff. If $\lambda = 0$, all actions are chosen with equal probabilities.

First, we illustrate the FRE predictions by plotting the predicted distribution of choices at various values of λ. Then, we evaluate the goodness of fit by fitting FRE to the experimental data and comparing the fit to QRE. From the definition of FRE, note that it is equivalent to the QRE of a modified game, in which game's payoffs $\pi_i(q_k, q_{-i})$ are replaced by the likelihood that an action is a best response, calculated by $b(q_k, q_{-i})$. We therefore calculate FRE using the same tracing procedure as in QRE, but using the modified game. Note that this modification leads to a significant loss of information about the incentives faced by the players.[25]

[25]It would be possible to develop a hybrid model of QRE and FRE, in which attractions are a convex combination of the monetary payoff and the best-response likelihood. However, such a model is beyond



(a) Standard treatments

(b) Normalized treatments

Figure C.1: FRE distribution with $\lambda = 8$. Vertical dashed lines indicate symmetric Nash equilibria.

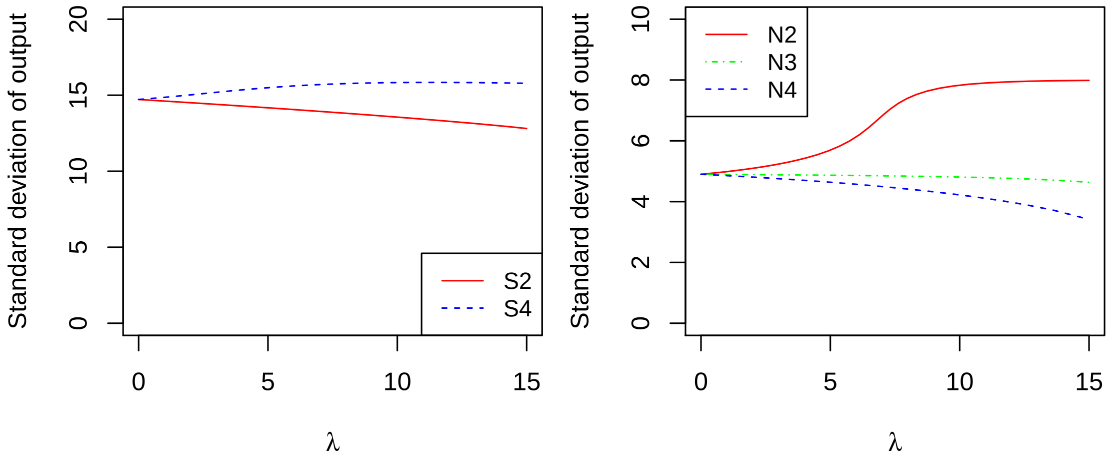
Figure C.1 shows the FRE choice probabilities for $\lambda = 8$. In standard treatments, S4 stands out due to the high predicted frequency of producing nothing, which is the best response when the total output of the other firms exceeds 80. In normalized treatments, the FRE choice distribution has a higher variance in smaller groups. N2 is notable due to a high predicted frequency of the two most extreme output levels. This prediction is explained by a higher likelihood of observing extreme average output in N2 than in N3 or N4, and a best-response function that makes the output of 8 optimal when the average output of the other firms exceeds 21, while 24 is optimal when it falls below 11. Overall, the direction of change in FRE choice distributions in normalized treatments reflects the empirical pattern. We further explore the differences in variance across group sizes by calculating the standard deviation of the choice distribution for λ values between 0 and 15. Figure C.2 shows that FRE correctly predicts that in the normalized treatments, the standard deviations is decreasing in group size.

Next, we fit FRE to the data using the method originally developed by Bajari and Hortacsu (2005). First, for each action, we calculate the expected likelihood of being the best response, assuming that the strategy profile of other players is generated by each player independently drawing their strategy from the empirically observed output distribution. The expected likelihoods are mapped into choice probabilities using the softmax function with parameter λ. We fit the model by estimating the value of λ that maximizes the likelihood of the empirical choice distribution.[26]

Table C.1 extends the results from Table 4, comparing the estimated values and

the scope of this paper.

[26]Note that the value of λ estimated in FRE cannot be compared to the λ values in QRE because the attractions in FRE are measured in likelihood (ranging from 0 to 1) while attractions in QRE represent the expected monetary earnings.



(a) Standard treatments (b) Normalized treatments

Figure C.2: Standard deviation of output in estimated FRE distributions for $\lambda \in [0, 15]$.

Table C.1: Goodness of fit and estimated parameter values in QRE and FRE.

	QRE				FRE			
	Separate		Combined		Separate		Combined	
	$\hat{\lambda}$	LL	$\hat{\lambda}$	LL	$\hat{\lambda}$	LL	$\hat{\lambda}$	LL
S2	1.395	-2739.97	1.497	-2740.34	13.63	-2665.76	7.84	-2701.296
S4	1.535	-4561.56	1.497	-4561.65	4.42	-4701.504	7.84	-4715.934
N2	-0.292	-5436.98	1.497	-5531.25	4.98	-5324.712	7.84	-5369.582
N3	2.507	-4014.05	1.497	-4024.05	14.68	-4001.647	7.84	-4018.677
N4	4.686	-5161.69	1.497	-5281.54	15.32	-5045.288	7.84	-5136.418
Total		-21914.25		-22138.83		-21738.91		-21941.91

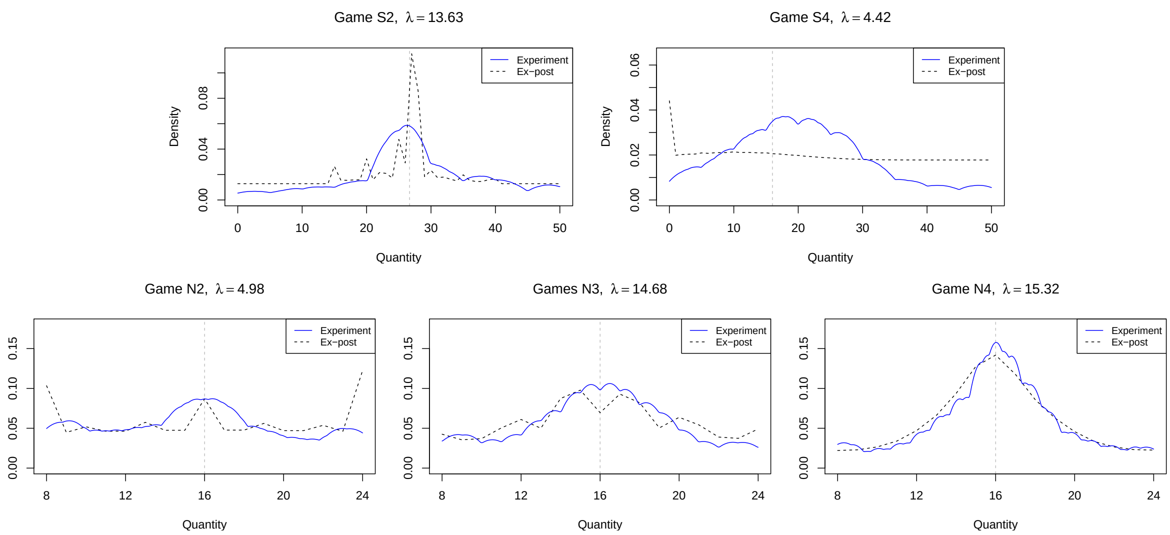


Figure C.3: Best-fitting FRE estimated separately for each treatment.

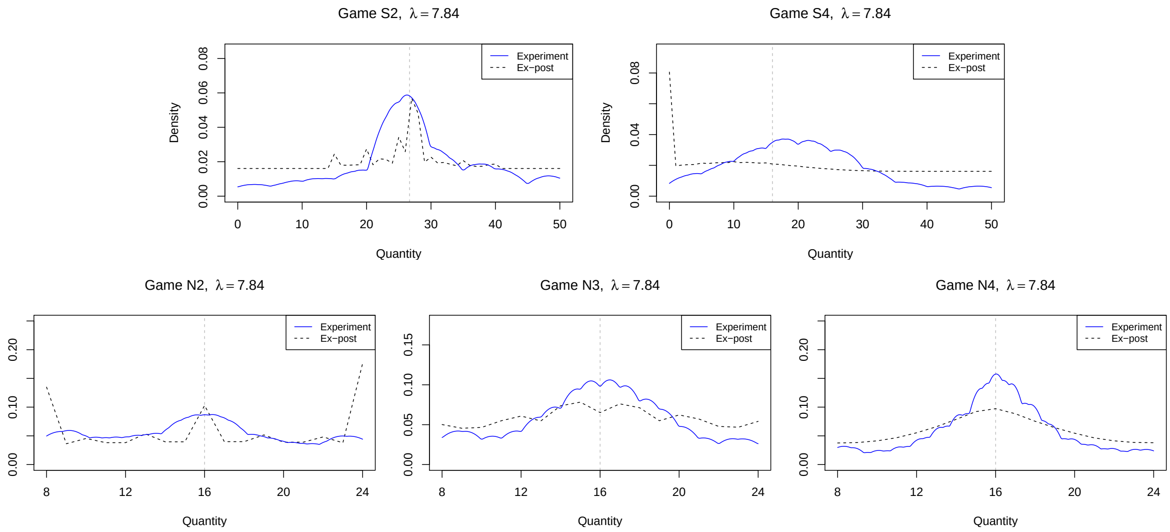


Figure C.4: Best-fitting FRE estimated for all treatments.

goodness of fit for QRE and FRE. Figures C.3 and C.4 illustrate the fit by comparing the choice probabilities in the best-fitting FRE to the kernel density estimates of the experimental data. Overall, FRE has a higher total log-likelihood than QRE, both when a separate model is estimated for each treatment and when a single model is estimated for all treatments. FRE also fits better in each individual game, except for S4. FRE fails to explain choices in S4 because it overestimates the frequency of choosing 0. In the experiment, participants would have maximized their round earnings by producing 0 each time the total output by other participants exceeded 80 (which happened in over 20% of the rounds), yet 0 was chosen only about 2% of the time. In the normalized treatments, predicted choice probabilities are close to the empirical data, although the estimated λ value is much lower in N2 than in N3 or N4. The higher estimated level of noise in N2 is again caused by FRE overestimating the frequency of the most extreme output levels. When λ is required to be the same in all five games, FRE can explain the increased variance in smaller groups of the normalized treatments, although the higher noise level needed to reduce the predicted frequency of the extreme choices in S4 and N2 reduces the goodness of fit in the other three treatments.

D Additional Results

Table D.1: Structure of all treatments that were run. This paper uses data only from the first block of 20 rounds. In games marked with I, the strategy space 8-24 was mapped into 0-16. In games marked with D, the strategy space was reversed before mapping into 0-16. Games marked with S use a standard Cournot oligopoly incentive structure with a strategy space 0-50. SC3 is a 3-person game of strategic complements, with either a strategy space 0-16 (SC3) or 0-50 (SC').

Treatment	1	2	3	4	5	6	7	8
Rounds 1-20	N2I	N4I	N3I	N2D	N4D	N3D	S2	S4
Rounds 21-40	N3I	N3I	SC3	N3D	N3D	SC3	S3	S3
Rounds 41-60	SC3	SC3	-	SC3	SC3	-	SC3'	SC3'
# Sessions	4	4	3	4	4	3	3	5
# Participants	48	48	36	48	48	36	36	60
# Markets in B1	24	12	12	24	12	12	18	15

Table D.2: Random effects GLS regression. Standard errors are clustered on the group level. Data from all rounds.

	Increasing			Decreasing		
	DV: r	DV: φ^N	DV: φ^W	DV: r	DV: φ^N	DV: φ^W
3-firm market	0.0412	-0.110	-0.0659	-0.0193	0.0516	0.0309
	(1.61)	(-1.61)	(-1.61)	(-0.44)	(0.44)	(0.44)
4-firm market	0.000326	-0.000868	-0.000521	0.0375	-0.1000	-0.0600
	(0.01)	(-0.01)	(-0.01)	(1.33)	(-1.33)	(-1.33)
1/Round	0.00697	-0.0186	-0.0112	-0.0834**	0.222**	0.133**
	(0.23)	(-0.23)	(-0.23)	(-2.82)	(2.82)	(2.82)
Constant	1.024***	-0.0651	0.361***	0.953***	0.124	0.475***
	(49.51)	(-1.18)	(10.90)	(34.52)	(1.69)	(10.74)
N	2640	2640	2640	2640	2640	2640

z statistics in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table D.3: Random effects GLS regression. Standard errors are clustered on the group level. Data from rounds 15-20.

	Standard			Normalized		
	DV: r	DV: φ^N	DV: φ^W	DV: r	DV: φ^N	DV: φ^W
3-firm market	–	–	–	0.0322	-0.0858	-0.0515
				(0.85)	(-0.85)	(-0.85)
4-firm market	0.182***	-0.418*	-0.571***	0.0256	-0.0683	-0.0410
	(3.79)	(-2.56)	(-8.07)	(0.93)	(-0.93)	(-0.93)
1/Round	1.861	-6.749	-2.619	-1.574	4.197	2.518
	(0.43)	(-0.53)	(-0.39)	(-1.15)	(1.15)	(1.15)
Decreasing				-0.0612*	0.163*	0.0979*
labels				(-2.40)	(2.40)	(2.40)
Constant	0.943***	0.187	0.750	1.112***	-0.300	0.220
	(3.64)	(0.24)	(1.87)	(13.82)	(-1.40)	(1.71)
N	576	576	576	1584	1584	1584

z statistics in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table D.4: Goodness of fit and estimated parameter values in QRE and FRE, separately for standard and normalized treatments.

	QRE		FRE	
Treatment	$\hat{\lambda}$	LL	$\hat{\lambda}$	LL
S2	1.482	-2740.24	8.28	-2696.34
S4	1.482	-4561.73	8.28	-4720.376
N2	1.526	-5534.16	7.70	-5365.159
N3	1.526	-4023.46	7.70	-4019.388
N4	1.526	-5279.18	7.70	-5139.97
Total		-22138.77		-21941.23

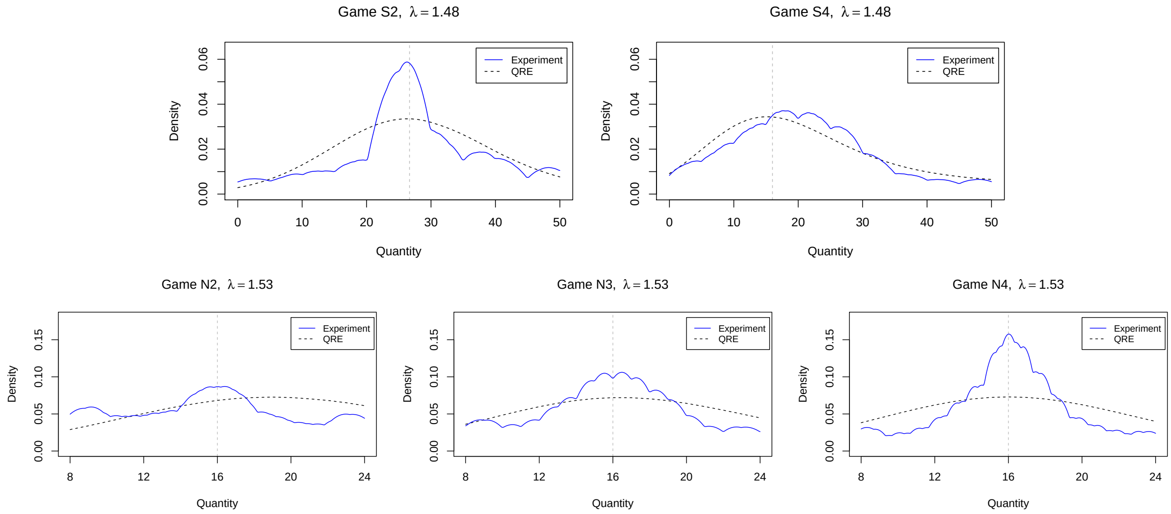


Figure D.1: Best-fitting QRE estimated separately for standard and normalized treatments (compared to kernel density).

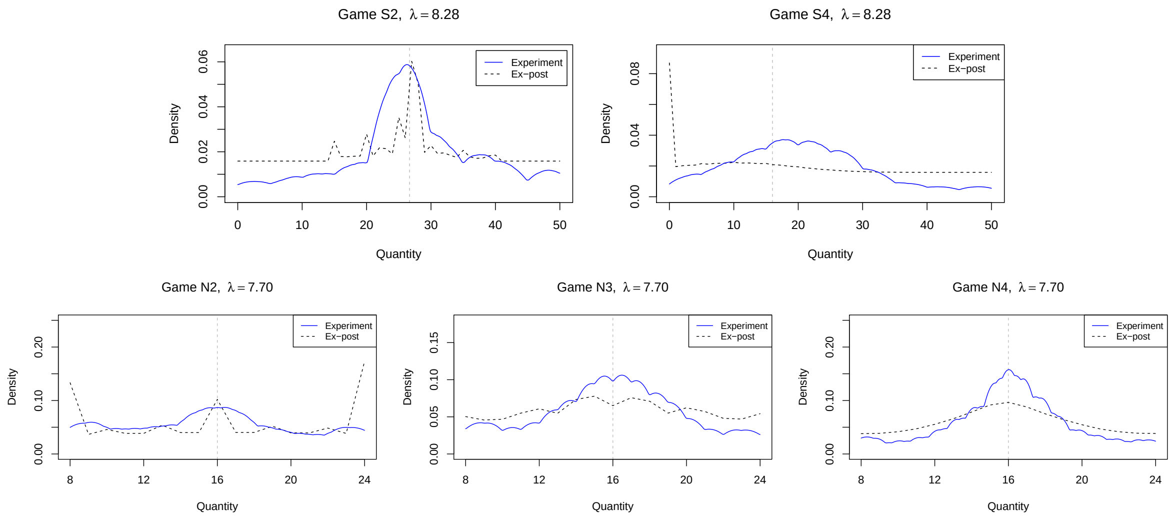


Figure D.2: Best-fitting FRE estimated separately for standard and normalized treatments (compared to kernel density).

E Instructions

The original French version of instructions is available on request. We provide an English translation below. We reproduce only the instructions for the treatments with the "normalized" design. The only difference in the instructions for the "standard" design is the cardinality of the strategy space: number "16" in highlighted places was replaced by "50".

GENERAL INSTRUCTIONS

Welcome to the Laboratory of Experimental Economics of Nice (LEEN – Nice Lab).

By agreeing to participate in this experiment, you agree with the regulations of the laboratory, which are available on our website or on request.

In this experiment your decisions will be anonymous and will partly determine your final payment, therefore read the following instructions carefully. The participation fee of 5 EUR is included in the payoff function. Your earnings will be paid to you individually and confidentially private once you complete a short questionnaire at the end of the experiment.

In this experiment you can earn money. During the experiment we will refer to ECU (Experimental Currency Unit) instead of EUR. The total amount of ECU that you will have earned during the experiment will be converted into cash and paid individually at the end of the experiment. The conversion rate used to convert your ECU into your cash payment will be **150 ECU = 1 EUR**.

We ask you not to communicate or to disturb the other participants. We also ask you to turn off your mobile phones and not use them during the experiment.

In these rules are not followed, the experiment may be stopped and all payments canceled.

If you encounter a technical problem, we ask you to raise your hand silently and wait for the experimenter.

All the participants with whom you interact during this experiment will receive the same instructions and participate in the same experiment.

DESCRIPTION OF THE EXPERIMENT

The experiment will have several parts. Each part will consist of 20 rounds. At the end of the experiment one round from each part will be randomly selected for payment. All rounds have an equal chance to be selected. Your earnings from the selected rounds will be added up, converted into cash and paid to you in private.

In each round you will be matched with other participants. At the start of each part you will be informed about how many participants you will be playing with. You will choose a number (between 0 and 16), which we will call "your action". Every other participant will choose an action at the same time. Your payoff will depend on your action and on the average action of all other participants with whom you were matched. In each round, you will have 30 seconds to make a decision. To make a choice, you must enter your action into the field at the top and click "OK" before the time runs out. The participants with whom you will interact will face the same task as you and will have the same information and payoff function. The task, the payoff function and the participants with whom you will interact will be the same in each round of one part. In each new part, you will play against participants with whom you did not interact in previous parts.

The exact way of how your payoff depends on your action and on the average action of other participants will be explained using a payoff table and a payoff calculator, which will be available on the computer screen when you will be making your decision.

- **The payoff table** shows your payoffs for some combinations of your action and the average action of other participants.
- **The payoff calculator** allows you to enter any action for yourself and an average action of other participants, and displays a payoff that you would receive in that case.

Starting from round 2, you will also be informed about your payoff in the previous round. Furthermore, you will have an option to view the following additional information:

1. **Average choices and their history.** This option gives you information about the average choice of other participants and your payoff in the previous round, as well as in all earlier rounds of that part.
2. **Individual choices and payoffs.** This option gives you information about the choices and payoffs of each member in your group, including yourself.

You will be able to switch between these options using buttons on your computer screen.

In addition, after the first round of each part we will ask you to guess the average action of other participants in that round. The closer your guess is to the average choice of other participants, the higher will be your payment. If your guess is G and the actual average action of other participants is D, your payment will be higher the smaller is the absolute difference between G and D (denoted $|G-D|$). In particular, your payoff will be: $\left(1-\frac{|G-D|}{16}\right)*100$ ECU. Notice that if your guess is exactly equal to the average choice ($G-D=0$), you will receive 100 ECU. At the end of the experiment one of these tasks will be randomly chosen. The payment from the chosen task will be added to your earnings.

At the end of all parts you will be informed about your payoff in ECU from the rounds that were randomly selected for payment. Payoff from these rounds will be summed up, converted into EUR and paid in private once you complete a short questionnaire. In the questionnaire you will have a chance to make additional income which will be added to your earnings. Please stay seated until we ask you to come to receive the earnings.

If you have any further questions, please raise your hand now. The experiment will start once everyone has finished reading the instructions.

F Payoff Tables

Table F.1: Payoffs in N2, N3 and N4 treatments.

	Average output chosen by opponents																
Output	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
8	514	490	466	442	418	394	370	346	322	298	274	250	226	202	178	154	130
9	553	526	499	472	445	418	391	364	337	310	283	256	229	202	175	148	121
10	590	560	530	500	470	440	410	380	350	320	290	260	230	200	170	140	120
11	625	592	559	526	493	460	427	394	361	328	295	262	229	196	163	130	119
12	658	622	586	550	514	478	442	406	370	334	298	262	226	190	154	118	118
13	689	650	611	572	533	494	455	416	377	338	299	260	221	182	143	117	117
14	718	676	634	592	550	508	466	424	382	340	298	256	214	172	130	116	116
15	745	700	655	610	565	520	475	430	385	340	295	250	205	160	115	115	115
16	770	722	674	626	578	530	482	434	386	338	290	242	194	146	114	114	114
17	793	742	691	640	589	538	487	436	385	334	283	232	181	130	113	113	113
18	814	760	706	652	598	544	490	436	382	328	274	220	166	112	112	112	112
19	833	776	719	662	605	548	491	434	377	320	263	206	149	111	111	111	111
20	850	790	730	670	610	550	490	430	370	310	250	190	130	110	110	110	110
21	865	802	739	676	613	550	487	424	361	298	235	172	109	109	109	109	109
22	878	812	746	680	614	548	482	416	350	284	218	152	108	108	108	108	108
23	889	820	751	682	613	544	475	406	337	268	199	130	107	107	107	107	107
24	898	826	754	682	610	538	466	394	322	250	178	106	106	106	106	106	106

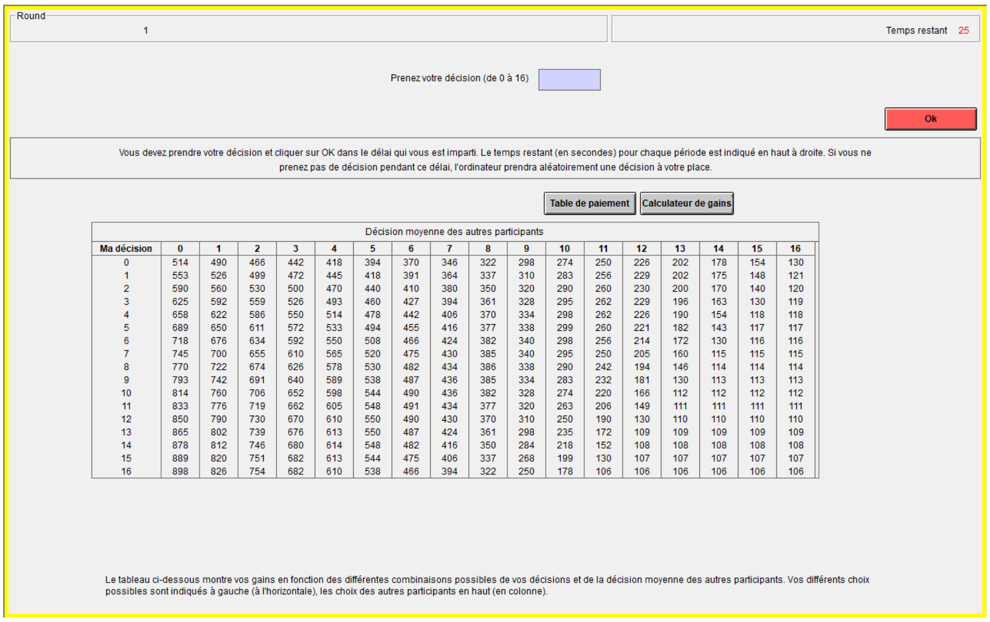
Table F.2: Payoffs in S2 treatment.

	Average output chosen by opponents																				
Output	0	2.5	5.0	7.5	10.0	12.5	15.0	17.5	20.0	22.5	25.0	27.5	30.0	32.5	35.0	37.5	40.0	42.5	45.0	47.5	50.0
0	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130
2.5	200	197	195	193	191	188	186	184	182	179	177	175	173	170	168	166	164	161	159	157	155
5	265	260	256	251	247	242	238	233	229	224	220	215	211	206	202	197	193	188	184	179	175
7.5	326	319	312	305	299	292	285	278	272	265	258	251	245	238	231	224	218	211	204	197	191
10	382	373	364	355	346	337	328	319	310	301	292	283	274	265	256	247	238	229	220	211	202
12.5	434	422	411	400	389	377	366	355	344	332	321	310	299	287	276	265	254	242	231	220	209
15	481	467	454	440	427	413	400	386	373	359	346	332	319	305	292	278	265	251	238	224	211
17.5	524	508	492	476	461	445	429	413	398	382	366	350	335	319	303	287	272	256	240	224	209
20	562	544	526	508	490	472	454	436	418	400	382	364	346	328	310	292	274	256	238	220	202
22.5	596	575	555	535	515	494	474	454	434	413	393	373	353	332	312	292	272	251	231	211	191
25	625	602	580	557	535	512	490	467	445	422	400	377	355	332	310	287	265	242	220	197	175
27.5	650	625	600	575	551	526	501	476	452	427	402	377	353	328	303	278	254	229	204	179	155
30	670	643	616	589	562	535	508	481	454	427	400	373	346	319	292	265	238	211	184	157	130
32.5	686	656	627	598	569	539	510	481	452	422	393	364	335	305	276	247	218	188	159	130	118
35	697	665	634	602	571	539	508	476	445	413	382	350	319	287	256	224	193	161	130	117	117
37.5	704	670	636	602	569	535	501	467	434	400	366	332	299	265	231	197	164	130	117	117	117
40	706	670	634	598	562	526	490	454	418	382	346	310	274	238	202	166	130	116	116	116	116
42.5	704	665	627	589	551	512	474	436	398	359	321	283	245	206	168	130	115	115	115	115	115
45	697	656	616	575	535	494	454	413	373	332	292	251	211	170	130	114	114	114	114	114	114
47.5	686	643	600	557	515	472	429	386	344	301	258	215	173	130	113	113	113	113	113	113	113
50	670	625	580	535	490	445	400	355	310	265	220	175	130	112	112	112	112	112	112	112	112

Table F.3: Payoffs in S4 treatment.

	Average output chosen by opponents																									
Output	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50
0	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130
2	286	274	262	250	238	226	214	202	190	178	166	154	142	130	128	128	128	128	128	128	128	128	128	128	128	128
4	434	410	386	362	338	314	290	266	242	218	194	170	146	126	126	126	126	126	126	126	126	126	126	126	126	126
6	574	538	502	466	430	394	358	322	286	250	214	178	142	124	124	124	124	124	124	124	124	124	124	124	124	124
8	706	658	610	562	514	466	418	370	322	274	226	178	130	122	122	122	122	122	122	122	122	122	122	122	122	122
10	830	770	710	650	590	530	470	410	350	290	230	170	120	120	120	120	120	120	120	120	120	120	120	120	120	120
12	946	874	802	730	658	586	514	442	370	298	226	154	118	118	118	118	118	118	118	118	118	118	118	118	118	118
14	1054	970	886	802	718	634	550	466	382	298	214	130	116	116	116	116	116	116	116	116	116	116	116	116	116	116
16	1154	1058	962	866	770	674	578	482	386	290	194	114	114	114	114	114	114	114	114	114	114	114	114	114	114	114
18	1246	1138	1030	922	814	706	598	490	382	274	166	112	112	112	112	112	112	112	112	112	112	112	112	112	112	112
20	1330	1210	1090	970	850	730	610	490	370	250	130	110	110	110	110	110	110	110	110	110	110	110	110	110	110	110
22	1406	1274	1142	1010	878	746	614	482	350	218	108	108	108	108	108	108	108	108	108	108	108	108	108	108	108	108
24	1474	1330	1186	1042	898	754	610	466	322	178	106	106	106	106	106	106	106	106	106	106	106	106	106	106	106	106
26	1534	1378	1222	1066	910	754	598	442	286	130	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104
28	1586	1418	1250	1082	914	746	578	410	242	102	102	102	102	102	102	102	102	102	102	102	102	102	102	102	102	102
30	1630	1450	1270	1090	910	730	550	370	190	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
32	1666	1474	1282	1090	898	706	514	322	130	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98	98
34	1694	1490	1286	1082	878	674	470	266	96	96	96	96	96	96	96	96	96	96	96	96	96	96	96	96	96	96
36	1714	1498	1282	1066	850	634	418	202	94	94	94	94	94	94	94	94	94	94	94	94	94	94	94	94	94	94
38	1726	1498	1270	1042	814	586	358	130	92	92	92	92	92	92	92	92	92	92	92	92	92	92	92	92	92	92
40	1730	1490	1250	1010	770	530	290	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90
42	1726	1474	1222	970	718	466	214	88	88	88	88	88	88	88	88	88	88	88	88	88	88	88	88	88	88	88
44	1714	1450	1186	922	658	394	130	86	86	86	86	86	86	86	86	86	86	86	86	86	86	86	86	86	86	86
46	1694	1418	1142	866	590	314	84	84	84	84	84	84	84	84	84	84	84	84	84	84	84	84	84	84	84	84
48	1666	1378	1090	802	514	226	82	82	82	82	82	82	82	82	82	82	82	82	82	82	82	82	82	82	82	82
50	1630	1330	1030	730	430	130	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80

G Screenshots



	Décision moyenne des autres participants																
Ma décision	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
0	514	490	466	442	418	394	370	346	322	298	274	250	226	202	178	154	130
1	553	526	499	472	445	418	391	364	337	310	283	256	229	202	175	148	121
2	590	560	530	500	470	440	410	380	350	320	290	260	230	200	170	140	120
3	625	592	559	526	493	460	427	394	361	328	295	262	229	196	163	130	119
4	658	622	586	550	514	478	442	406	370	334	298	262	226	190	154	118	118
5	689	650	611	572	533	494	455	416	377	338	299	260	221	182	143	117	117
6	718	676	634	592	550	508	466	424	382	340	298	256	214	172	130	116	116
7	745	700	655	610	565	520	475	430	385	340	295	250	205	160	115	115	115
8	770	722	674	626	578	530	482	434	386	338	290	242	194	146	114	114	114
9	793	742	691	640	589	538	487	436	385	334	283	232	181	130	113	113	113
10	814	760	706	652	598	544	490	436	382	328	274	220	166	112	112	112	112
11	833	776	719	662	605	548	491	434	377	320	263	206	149	111	111	111	111
12	850	790	730	670	610	550	490	430	370	310	250	190	130	110	110	110	110
13	865	802	739	676	613	550	487	424	361	298	235	172	109	109	109	109	109
14	878	812	746	680	614	548	482	416	350	284	218	152	108	108	108	108	108
15	889	820	751	682	613	544	475	406	337	268	199	130	107	107	107	107	107
16	898	826	754	682	610	538	466	394	322	250	178	106	106	106	106	106	106

Figure G.1: Payoff table in normalized treatments.

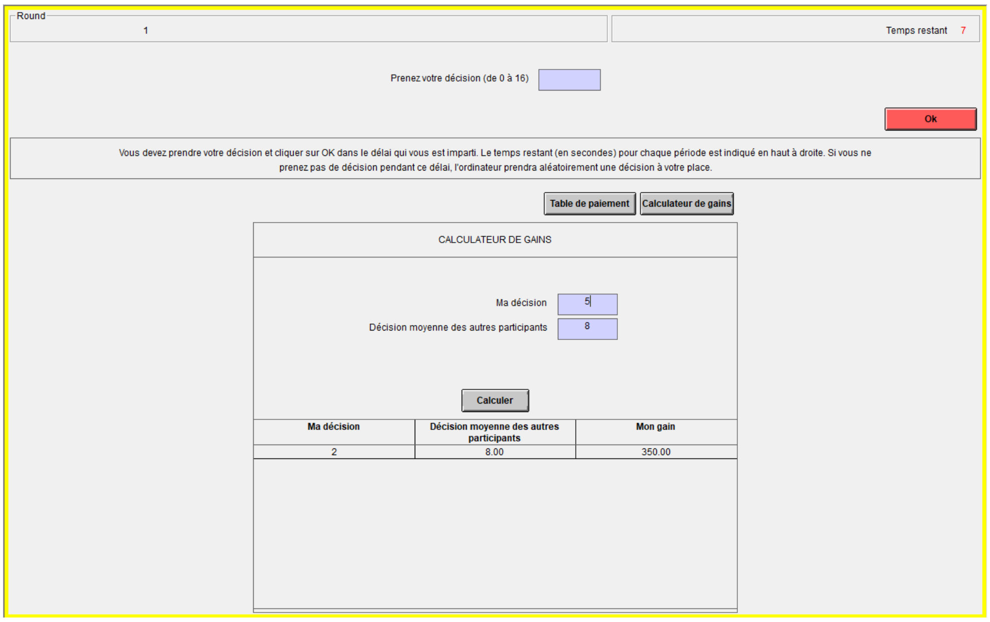


Figure G.2: Payoff calculator in normalized treatments.

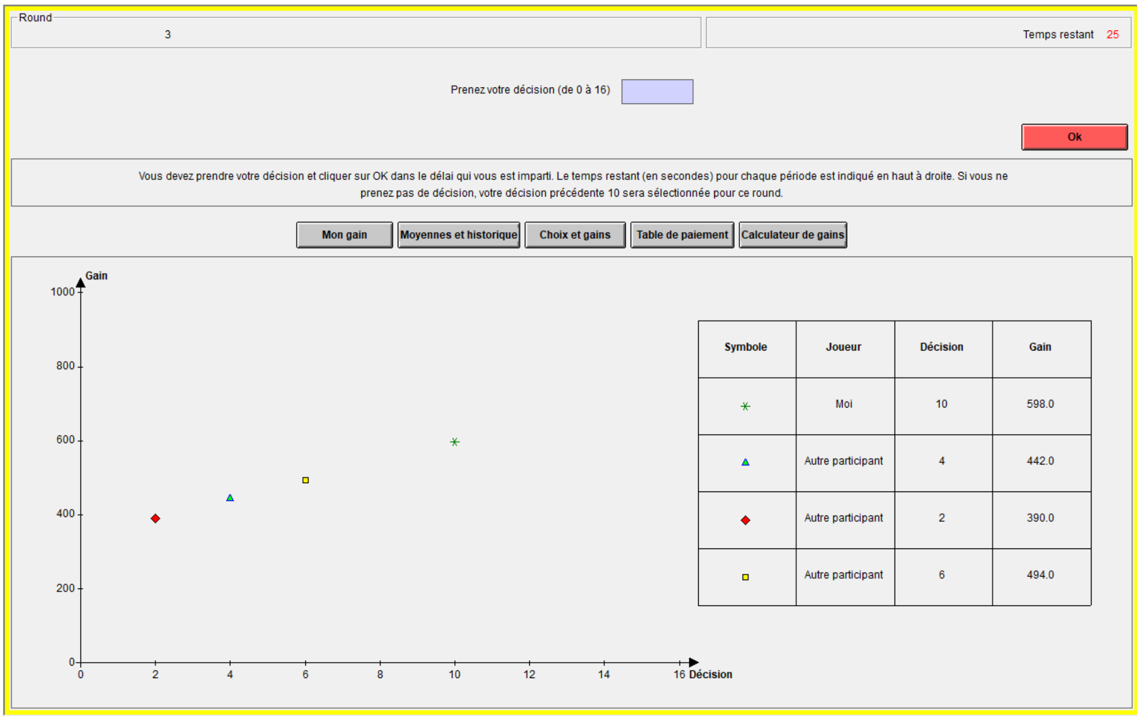


Figure G.3: Feedback about individual choices and payoffs in normalized treatments.

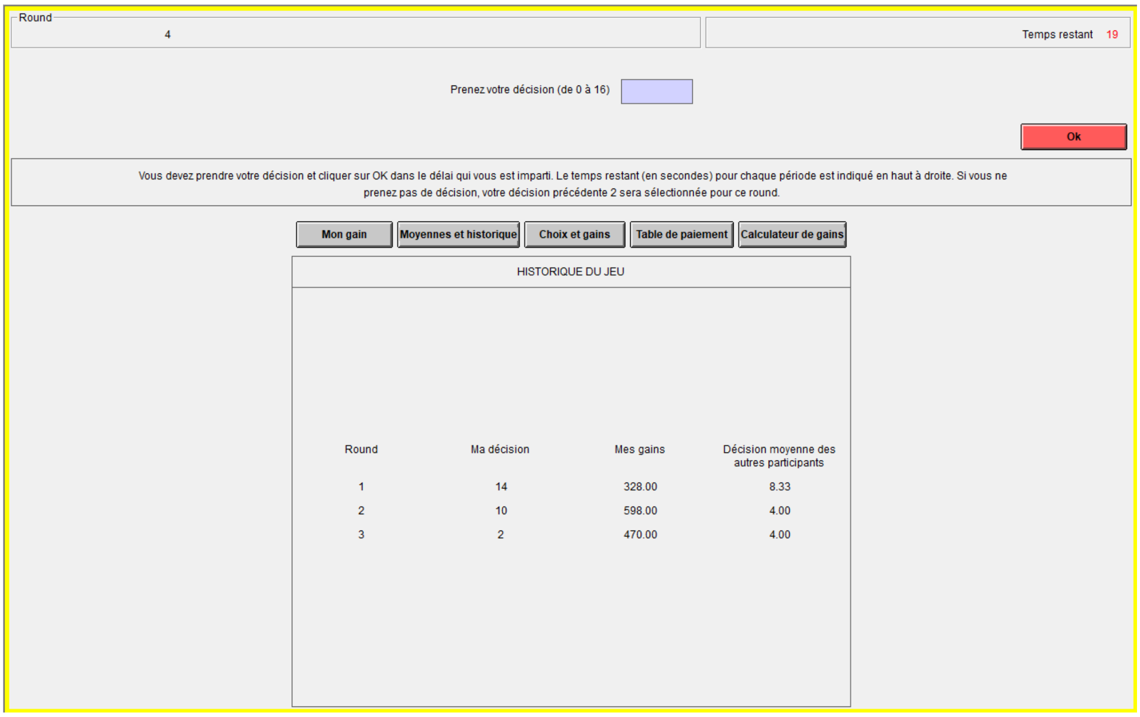


Figure G.4: Feedback about the history of own choices and payoffs in previous rounds.