Number Effects and Tacit Collusion in Experimental Oligopolies*

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Abstract

We systematically investigate the relationship between the number of firms in a market and tacit collusion by means of a meta-analysis of the literature on oligopoly experiments as well as two own experiments with a total of 368 participants. We show that the degree of tacit collusion decreases strictly with the number of competitors in industries with two, three and four firms. Although previous literature could not affirm that triopolies are more collusive than quadropolies, we provide evidence for this fact for symmetric and asymmetric firms under Bertrand and Cournot competition. (*JEL* L13, D21, D43, C92)

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1 Introduction

In general the number of firms in a specific market is determined endogenously by the competitive process and particularly by firms' entry and exit decisions. However, in merger control and regulatory proceedings, authorities are often required to determine a specific number of competitors exogenously. This makes it necessary to estimate the number effects on the competitiveness of a market. Obviously, markets in practice exhibit many idiosyncrasies that impact competitiveness and require a case-by-case analysis before a merger can be cleared or before regulatory remedies are imposed or lifted. Yet, a general relationship between the number of competitors and the competitiveness of a given market, above and beyond any market peculiarities, is frequently assumed. To this end, it is well known that equilibrium predictions for market prices are generally decreasing with a higher number of competitors. However, the impact on the *degree of tacit collusion*, i.e., the ability of firms to sustain supra-competitive prices above the equilibrium price, is not as clear.

In this article, we investigate the research hypothesis that tacit collusion in oligopolistic markets with two, three, and four competitors, everything else being equal, decreases strictly monotonically with the number of competing firms. From a methodological point of view, experimental laboratory experiments are well suited to address this question, because they allow to observe out-of-equilibrium behavior while controlling for environmental conditions. In this context, it has previously been concluded that tacit collusion is "frequently observed with two sellers, rarely in markets with three sellers, and almost never in markets with four or more sellers" (Potters and Suetens, 2013, p.17). Surprisingly, our review of the extant experimental literature shows that there is actually no robust empirical evidence that would support this claim of a strictly monotonic relationship between the number of firms and the degree of tacit collusion in a given market. Whereas a meta-analysis of the extant literature supports the notion that duopolies are significantly more prone to tacit collusion than quadropolies, i.e., that "two are few and four are many" (Huck et al., 2004, p.435), there is no empirical support for a significant effect when moving from *four to three* firms. However, the lack of statistical power across and within existing studies precludes a conclusive evaluation of a strictly monotonic relationship between the number of firms and the degree of tacit collusion in a market. Moreover, the review of the extant literature reveals a lack of systematic evaluation of such number effects under different competition models (Cournot vs. Bertrand), with symmetric and asymmetric firms, and under consideration of different theoretical equilibrium predictions (Nash vs. Walras). Therefore, we conduct two own laboratory experiments, which are explicitly designed to systematically test for number effects on tacit collusion under price and quantity competition, as well as with symmetric and asymmetric firms. At the same time, we hold all other environmental conditions (e.g., equilibrium profits) fixed. Thereby, we do find a significant increase in tacit collusion from *four to three* firms as well as from *three to two* firms. In fact, the empirically observed increase of tacit collusion is almost identical from four to three as from three to two, suggesting a *linear number effect* for highly concentrated oligopolies with regard to the (in)ability to coordinate on a price level above the theoretical Nash prediction.

In practice, concerns about market power and coordinated behavior frequently confront competition and regulatory authorities with the question: *How many competitors are enough to ensure competition*? For example, several high-profile merger control proceedings in the European Union[1] as well as in the US[2] have dealt with cases that would reduce the remaining number of competitors from four to three major mobile telecommunications operators in the respective relevant market. Also, in the US airline industry, the Department

[1]Hutchinson 3G Austria / Orange Austria (European Commission, 2012), Telefónica Deutschland / E-Plus (European Commission, 2014a), Hutchinson 3G UK / Telefónica Ireland (European Commission, 2014b).

[2]AT&T / T-Mobile US (Federal Communications Commission, 2011), Sprint Corp / T-Mobile US (Federal Communications Commission, 2014).

of Justice had initially filed a lawsuit to block the merger between American Airlines and US Airways that reduced the number of legacy carriers from four to three, explicitly referring to the low number of competitors as a critical threat to effective competition (Stewart, 2013). Even in a high-tech commodity industry like the hard disk drive industry, consolidation among manufacturers raises the question whether there is a magical number to reconcile scale synergies and pro-competitive effects (Igami and Uetake, 2015). Similar to competition authorities, sector-specific regulatory agencies implicitly or explicitly examine the sufficient number of competitors when assessing the need for ex ante access regulation. For instance, geographically segmented deregulation of the wholesale broadband access market in the UK is conditioned on the number of active competitors in a region (Ofcom, 2014). Likewise, in media retail markets, which in some countries are characterized by repeated direct public intervention, competition authorities are required to determine the sufficient number of local sellers to achieve sustainable coverage in combination with competitive prices (Balmer, 2013).

The remainder of this article is organized as follows. Next, in Section 2 we present a review and meta-analysis of the extant experimental literature. In Sections 3 and 4 we report the design and results of the experiments with symmetric and asymmetric firms, respectively. Section 5 discusses the findings pooled over all three studies and highlights their policy implications for both antitrust and regulatory policy.

2 Review and meta-analysis of the experimental literature

In a study based on field data, Davies et al. (2011) try to identify structural determinants of tacit collusion by examining decisions on coordinated effects in European merger control cases. Whereas these results point to higher tacit collusion (concerns) in duopoly markets, no conclusions can be drawn with regard to the general relationship between the number of firms and tacit collusion, because the data includes few markets with three firms and only one with four firms. Moreover, the indirect identification approach relies on the assumption that the European Commission is correct in the ex ante assessment of tacit collusion, but it cannot directly measure whether tacit collusion actually occurs empirically.

Thus, in order to investigate the general relationship between the number of competitors and the competitiveness in a given market directly, economic laboratory experiments are particularly well suited, because they allow to identify systemic effects and to isolate distinct sources for tacit collusion through controlled variation of exogenous variables. In particular, experiments allow to isolate the effect of the number of competitors on firms' ability to coordinate through randomization and the control to hold constant any potential confounding variable. Hence, the experimental method avoids endogeneity concerns (e.g., of the observed number of competitors) inherent to field data (Angrist and Pischke, 2010), which are especially pronounced in the context of the structure-conduct-performance paradigm (Scherer and Ross, 1990; Schmalensee, 1990) of industrial organization. Moreover, empirical field studies are naturally framed in a specific market context and are thus neither generalizable per se nor directly applicable to other market scenarios as causal relationships are inherently difficult to prove (see Einav and Levin, 2010, for a discussion of the generalizability of empirical industry studies). Particularly with regard to the issue of tacit collusion, which is notoriously hard to detect in field studies, laboratory experiments can provide general insights by analyzing in- and out-of-equilibrium strategies and respective market outcomes relative to benchmark equilibria predicted by economic theory.

Consequently, it is not surprising that there are several experimental studies that investigate the drivers and impediments of tacit collusion in oligopolies. In their overview of these experiments, Potters and Suetens (2013, p. 17) conclude that "the scope of collusion is strongly affected by the number of competitors". With respect to the effect of the number of competitors on tacit collusion, Potters and Suetens suggest a strictly monotonic relationship, referring to individual experimental studies that have employed posted-offer markets, Bertrand competition, or Cournot competition. Although several of these studies find that tacit collusion is generally lower for a larger number of competitors, e.g., in markets with four relative to two competitors (e.g., Huck et al., 2004; Orzen, 2008), as described above, we highlight in the following that evidence for the stipulated monotonic number effect is scarce, in particular with regard to the assessment of tacit collusion in markets with three and four competitors.

2.1 Experimental designs

Most oligopoly experiments implement one of the two workhorse models in industrial organization: price competition à la Bertrand (Fouraker and Siegel, 1963; Dolbear et al., 1968; Dufwenberg and Gneezy, 2000; Orzen, 2008; Davis, 2009; Fonseca and Normann, 2012) or quantity competition à la Cournot (Fouraker and Siegel, 1963; Bosch-Domènech and Vriend, 2003; Huck et al., 2004; Waichman et al., 2014).[3] A third strand of literature observes tacit collusion in posted-offer markets, i.e., simultaneous competition in prices and quantities (Ketcham et al., 1984; Alger, 1987; Brandts and Guillén, 2007; Ewing and Kruse, 2010). As the latter experiments use very diverse models they are hardly comparable to one another and hence not considered in the following meta-analysis. Instead, the focus here is on oligopoly experiments with either price or quantity competition and constant marginal costs, which vary the number of competitors n in a market in one way or another. Table 1 lists the 10 experimental studies surveyed in this meta-analysis.

Six experiments employ price competition. Four of those investigate homogeneous

[3]Note that merger experiments induce asymmetry exogenously (see Götte and Schmutzler, 2009, for a comprehensive review) or endogenize merger formation which yields asymmetric markets post-merger (Lindqvist and Stennek, 2005). In order to prevent path dependencies from merger formation, only data from those experimental studies that vary the number of competing firms exogenously across treatments is used for this meta-analysis.

Table 1: Economic laboratory experiments that vary the number of competing firms.

Study	Competition	Information: Complete	Information: Perfect	Matching	n
		Bertrand (price) competition			
Fouraker and Siegel (1963)	Homogeneous	✓	✓/ ✗	Partner	$\{2,3\}$
Dolbear et al. (1968)	Differentiated	✓/ ✗	✓	Partner	$\{2,4,16\}$
Dufwenberg and Gneezy (2000)	Homogeneous	✓	✓	Stranger	$\{2,3,4\}$
Orzen (2008)	Differentiated	✓	✓	Partner, Stranger	$\{2,4\}$
Davis (2009)	Homogeneous	✓/ ✗	✓	Partner	$\{2,3,4\}$
Fonseca and Normann (2012)	Homogeneous	✓	✓	Partner	$\{2,4,6,8\}$
		Cournot (quantity) competition			
Fouraker and Siegel (1963)	Homogeneous	✓	✓/ ✗	Partner	$\{2,3\}$
Bosch-Domènech and Vriend (2003)	Homogeneous	✓/ ✗	✓	Partner	$\{2,3\}$
Huck et al. (2004)	Homogeneous	✓	✓/ ✗	Partner	$\{2,3,4,5\}$
Waichman et al. (2014)	Homogeneous	✓	✓/ ✗	Partner	$\{2,3\}$

✓: applicable — ✗: not applicable — ✓/ ✗: both (as treatment variable)

Bertrand competition, i.e., firms' products are perfect substitutes. The remaining two experiments use differentiated price competition, i.e., competitors' products are differentiated with regard to quality or consumers have heterogeneous preferences: Dolbear et al. (1968) consider a model in which the cross-price elasticity is half the own-price elasticity and Orzen (2008) models a fraction of consumers to be price-insensitive "convenience shoppers" (Orzen, 2008, p. 392). All of the four quantity competition experiments included in this meta-analysis employ a homogeneous Cournot model.

Experiments differ further in the amount of information provided to participants. In a situation of complete information, each firm, represented by an individual participant, knows about (or can retrieve) the cost and demand function of all firms in the market. Moreover, a firm with perfect information can observe all decisions made by its competitors, and hence, has knowledge over the full history of the game. Lastly, all but one study employ a fixed matching of firms over the entire time horizon. Instead, Dufwenberg and Gneezy (2000) match firms randomly in each period. Orzen (2008) additionally compares partner and stranger matching in a between-subject manner.

2.2 Measuring competitiveness as the degree of tacit collusion

In order to compare number effects on competitiveness or likewise, tacit collusion, across heterogeneous data sets from different experimental designs, a uniform performance criterion is required. As absolute price or quantity levels are inconclusive across experiments, different metrics are proposed in the extant literature to measure competitiveness in experimental oligopoly outcomes. For a review of Cournot experiments, Huck et al. (2004) report the ratio between a market's average total quantity $\overline{Q}$ and the total Nash quantity Q^{Nash}, $r = \overline{Q}/Q^{Nash}$. However, as Engel (2007, p. 494) points out, r is "sensitive to arbitrary changes in the level of $Q^{N[ash]}$". In addition, the measure is not well suited to quantify and compare non-equilibrium outcomes between treatments and experimental designs, because it does not incorporate the joint profit maximizing (JPM) quantity as a second benchmark.

Therefore, we employ the index proposed by Engel (2007) and Suetens and Potters (2007), and measure tacit collusion as the relative deviation of average price from the theoretical equilibrium $E \in \{Nash, Walras\}$ towards the JPM price p^{JPM}. Formally,

$$\varphi^E = \frac{\overline{p} - p^E}{p^{JPM} - p^E}.$$

In this vein, φ^E represents the *degree of tacit collusion* based on prices as compared to either the Nash equilibrium or the Walrasian (competitive) equilibrium as the theoretical prediction. The Walrasian equilibrium assumes all competitors to be price-takers and thus, under homogeneous Bertrand competition the Nash prediction and the Walrasian prediction coincide. Moreover, under some regularity conditions, Walrasian prices cannot exceed Nash prices in any oligopoly competition model, i.e., $p^{Walras} \leq p^{Nash}$. If $\varphi^E = 0$, the average market price $\overline{p}$ corresponds to the theoretical prediction by the equilibrium concept E. If $\varphi^E = 1$, the market is completely collusive and competitors behave like a hypothetical monopolist. Note that φ^E may exceed one if joint profit is not monotonic in prices. Furthermore, the measures' lower limits depend on the experimental design. Suetens and Potters (2007) employ the same measure based on Nash predictions of the stage game in their meta-study to investigate relative differences of tacit collusion under Bertrand and Cournot competition.[4]

In addition, Friedman (1971) suggests a theoretical benchmark to assess the likelihood "that tacit collusion can be sustained as an equilibrium in an infinitely repeated game context as part of a grim trigger strategy" (Suetens and Potters, 2007, p. 73), which is given by $F = \frac{\Pi^{JPM} - \Pi^{Nash}}{\Pi^{Defect} - \Pi^{JPM}}$ with Π^{Defect} as the maximum profit for a firm that unilaterally deviates from a collusive agreement. Hence, the Friedman index measures the incentive to collude implicitly by comparing the collusive markup on the Nash profit to the additional profit for defecting from coordination. In repeated oligopoly experiments each firm has to trade off short-term profits from deviating to foregone profits in future periods. The higher the Friedman index, the less profitable a deviation from a collusive agreement.[5] Although the Friedman index assumes an infinitely repeated game, it may nonetheless be informative in the context of finitely repeated games in experiments with fixed lengths across treatments as it is well-known that tacit collusion is no phenomenon that is limited to experiments with random termination rules.

2.3 Results of the meta-analysis

Table 2 reports the number of independent observations N and the two collusion metrics φ^E, as well as the Friedman index, F, for all experiments and treatments considered in this meta-analysis.[6] The following analysis is carried out in two steps: At first we consider

[4] Suetens and Potters (2007) exclude negative prices in Cournot experiments from their calculation of the degree of tacit collusion. In this meta-analysis, however, negative prices are considered as well, as they reflect the high competitiveness of excess capacity in Cournot markets.

[5] For Orzen (2008), the Friedman index has to be averaged over all three successive phases in each treatment in order to gain a single index value.

[6] The original experimental data is either collected from tables in the respective study, downloaded from an online repository, or provided by the authors. One exception is Bosch-Domènech and Vriend (2003) for

Table 2: Degrees of tacit collusion in economic laboratory experiments that vary the number of competing firms.

Study	Treatment	Periods†	n	N	φ^{Nash}	φ^{Walras}	F
	Bertrand (price) competition						
Fouraker and Siegel (1963)	Complete information	$[1,15] \in [1,15]$	2	17	0.412	0.412	0.766
			3	10	0.039	0.039	
	Incomplete information	$[1,15] \in [1,15]$	2	17	0.149	0.149	0.766
			3	11	0.019	0.019	0.311
Dolbear et al. (1968)	Complete information	$[8,12] \in [1,15]$	2	18	0.300	0.500	1.250
			4	9	−0.040	0.257	1.250
Dufwenberg and Gneezy (2000)	2/3/4	$[1,10] \in [1,10]$	2	12	0.260	0.260	1.000
			3	8	0.067	0.067	0.497
			4	6	0.077	0.077	0.331
Orzen (2008)	Fixed matching	$[1,90] \in [1,90]$	2	6	0.352	0.604	0.624
			4	6	−0.025	0.381	0.206
	Random matching	$[1,90] \in [1,90]$	2	6	0.113	0.462	0.624
			3	6	−0.008	0.391	0.206
Davis (2009)	2np/3np/4np	$[1,220] \in [1,220]$	2	6	0.113	0.113	0.754
			3	6	0.006	0.006	0.376
			4	6	0.006	0.006	0.251
Fonseca and Normann (2012)	NoTalk	$[1,29] \in [1,29]$	2	6	0.504	0.504	1.020
			4	6	0.060	0.060	0.338
			6	6	0.025	0.025	0.202
			8	6	0.011	0.011	0.145
	Cournot (quantity) competition						
Fouraker and Siegel (1963)	Complete information	$[1,22] \in [1,22]$	2	16	−0.244	0.585	1.000
			3	11	−0.266	0.367	0.750
	Incomplete information	$[1,22] \in [1,22]$	2	16	−0.114	0.629	1.000
			3	11	−0.260	0.370	0.750
Bosch-Domènech and Vriend (2003)	Easy	$[1,22] \in [1,22]$	2	9	0.296	0.765	0.889
			3	6	−0.176	0.451	0.732
	Hard	$[1,22] \in [1,22]$	2	9	−0.159	0.614	0.889
			3	6	−0.107	0.484	0.732
	Hardest	$[1,22] \in [1,22]$	2	9	−0.164	0.612	0.889
			3	6	−0.491	0.304	0.732
Huck et al. (2004)	Unified frame	$[1,25] \in [1,25]$	2	6	0.403	0.801	0.889
			3	6	0.032	0.516	0.750
			4	6	0.065	0.439	0.640
			5	6	−0.109	0.260	0.556
Waichman et al. (2014)	DSNC/TSNC	$[1,17] \in [1,17]$	2	12	−0.154	0.615	0.889
			3	13	−0.265	0.367	0.750
	DMNC/TMNC	$[1,17] \in [1,17]$	2	10	−0.046	0.651	0.889
			3	11	−0.062	0.469	0.750

† Periods used to compute the average degree of tacit collusion. If possible, data from all periods is used.

only number effects within a single study (intra-study). Subsequently, tacit collusion in duopolies, triopolies, and quadropolies is compared across all studies (inter-study).

Result 1 *Within and across the surveyed oligopoly experiments, markets with two firms are significantly more prone to tacit collusion than markets with three as well as four firms, everything else being equal. However, no significant difference in the degree of tacit collusion can be found between three and four firms.*

With respect to the intra-study analysis, data on the level of independent observations could be obtained for five experiments.[7] Table 3 provides p values from one-tailed non-parametric Mann-Whitney U tests of intra-study number effects on tacit collusion in these experiments. Following the hypothesis of a strictly monotonic relationship, the null hypothesis is that tacit collusion is always higher in a market with more firms. With the exception of the metrics based on Nash predictions for Fouraker and Siegel's (1963) Cournot treatments, all test results indicate that tacit collusion is higher in duopolies than in triopolies (2 vs. 3) or quadropolies (2 vs. 4) at the 5% level of significance. However, triopolies are not found to be more prone to tacit collusion than quadropolies (3 vs. 4), neither under Bertrand competition nor under Cournot competition.

For inter-study comparisons we focus on the most comparable treatments between studies in an effort to rule out any other explanations for differences other than the number of competitors. Thus, only treatments with complete and perfect information are considered for the following analysis.[8] Consequently, there are 10 independent duopoly observations, seven independent triopoly observations, and six independent quadropoly

which the data is retrieved from figures.

[7] We thank Hans-Theo Normann and Henrik Orzen for providing the experimental data used in Huck et al. (2004) and Orzen (2008), respectively.

[8] The following treatments reported in Table 2 are *not* considered in this step of the inter-study analysis: Incomplete information (Fouraker and Siegel, 1963), Random matching (Orzen, 2008), Hard and Hardest (Bosch-Domènech and Vriend, 2003), and DMNC/TMNC in which participants are managers instead of students (Waichman et al., 2014).

Table 3: Intra-study one-tailed Mann-Whitney U tests and associated p values.

Study	Treatment	n	φ^{Nash}	φ^{Walras}
	Bertrand (price) competition			
Fouraker and Siegel (1963)	Complete information	2 vs. 3	< 0.001	< 0.001
	Incomplete information	2 vs. 3	0.003	0.003
Orzen (2008)	Fixed matching	2 vs. 4	0.005	0.005
	Random matching	2 vs. 4	0.002	0.002
Davis (2009)	2np/3np/4np	2 vs. 3	0.008	0.008
		2 vs. 4	0.008	0.008
		3 vs. 4	0.437	0.437
	Cournot (quantity) competition			
Fouraker and Siegel (1963)	Complete information	2 vs. 3	0.294	0.008
	Incomplete information	2 vs. 3	0.084	< 0.001
Huck et al. (2004)	Unified frame	2 vs. 3	0.019	0.004
		2 vs. 4	0.019	0.002
		3 vs. 4	0.261	0.261

observations. As there is only a single observation for any $n > 4$ the statistical analysis is limited to markets with $n \in \{2, 3, 4\}$ firms. First, we note that the Friedman index, which is suggested to assess the likelihood of tacit collusion, predicts poorly if correlated with φ^{Nash} ($\rho = 0.213, p = 0.330$), but is positively and significantly correlated with φ^{Walras} ($\rho = 0.593, p = 0.003$). Second, in order to control for potential dependencies between treatments from the same study, i.e., different base levels of tacit collusion between experimental settings, the following three-level linear random-intercept model is estimated:

$$\begin{aligned}\varphi^{E}_{s,m,n} = {} & \beta_0 + \xi_s + \zeta_m \\ & + \beta_{Duopoly} \cdot Duopoly \\ & + \beta_{Quadropoly} \cdot Quadropoly \\ & + \beta_{Cournot} \cdot Cournot \\ & + \epsilon_{s,m,n},\end{aligned}$$

where $\varphi^{E}_{s,m,n}$ is the average degree of tacit collusion φ^{E} of markets with n competitors under model $m \in \{Bertrand, Cournot\}$ in study s, ζ_m is the error component shared between observations of the same model in study s (see Bertrand and Cournot treatments in Fouraker and Siegel, 1963), and ξ_s is the error component shared between observations from the same study. The results, as portrayed in Table 4, confirm the insight of the above intra-study findings that there is significantly more tacit collusion in duopolies compared to triopolies and quadropolies. Furthermore, there is no significant difference in tacit collusion between triopolies and quadropolies. In particular, the degree of tacit collusion is, on average, 26 percentage points (pp) higher in duopolies than triopolies according to both collusion measures. The same does not hold for the comparison between markets with three and markets with four firms as triopolies are found to have, on average, an almost identical degree of tacit collusion than quadropolies.[9]

Also notice that the regression analysis replicates the finding by Suetens and Potters (2007) that *Bertrand colludes more than Cournot*—however, only if tacit collusion is based on Nash predictions. In contrast, when compared to the Walrasian equilibrium, this effect is significant in the opposite direction. Thus, if a competitive market outcome where price equals marginal cost represents the benchmark for the degree of tacit collusion, *Cournot may collude more than Bertrand.* This finding can be explained by the fact that under Bertrand competition the Nash and Walrasian equilibrium do not differ as much (in fact are identical to each other in case of homogeneous Bertrand competition) as under Cournot competition. In consequence, everything else being equal, the Nash-based and Walrasian-based degree of tacit collusion under Bertrand competition only differ in case of differentiated goods, but the Walrasian-based degree of tacit collusion is much higher than the Nash-based degree of tacit collusion under Cournot competition (see Table 2).

All these results hold based on an average of the degrees of tacit collusion of all treat-

[9]These findings with regard to number effects hold also if we control for the heterogeneity across studies by means of a fixed effects model (instead of a random-intercept model) as shown by the estimated coefficients denoted in Table F4. Note that in this case we cannot control for the competition model due to perfect collinearity of the study fixed effects with the Cournot dummy.

Table 4: Multilevel mixed-effects linear regressions of tacit collusion on number of competitors and competition model on the basis of most comparable treatments.

Covariate	(1) φ^{Nash}	(2) φ^{Walras}
Duopoly	0.259***	0.261***
	(0.048)	(0.031)
Quadropoly	−0.020	−0.003
	(0.060)	(0.039)
Cournot	−0.227**	0.263***
	(0.088)	(0.050)
Constant	0.056	0.156***
	(0.067)	(0.049)
Studies	9	9
Models	10	10
Observations	23	23

Baseline: Bertrand triopoly.
Standard errors in parentheses.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

ments in a study with the same competition model and two, three, or four firms, respectively, i.e., if not only the most comparable treatments are considered but if an average is calculated over those treatments that vary a different design element than the competition model or the number of firms (see Table F1 for results of the respective multilevel mixed-effects regressions).[10] Furthermore, these findings can also be replicated by a meta-regression, a method vastly used in medical research (see, e.g., Higgins and Thompson, 2002), which takes into account the reliability of sample means from different studies by controlling for study-specific standard errors (see Appendix B for a presentation and discussion of estimates).

Although the previous analyses control for different base levels of tacit collusion between experiments via multilevel mixed-effects regressions as well as for the reliability of sample means via meta-regressions, the data used in the previous regression models are unbalanced

[10]Likewise, as shown in Table F3, the estimated effects are robust if we consider only studies that employ fixed matching of firms, i.e., if we do not include the treatments ran by Dufwenberg and Gneezy (2000) in our sample of most comparable treatments.

Table 5: Inter-study average degrees of tacit collusion and one-tailed matched-samples Wilcoxon signed-rank tests on the basis of most comparable treatments.

	Studies	φ^{Nash}	φ^{Walras}
2 vs. 3			
Duopoly	7	0.155	0.507
Triopoly	7	−0.081	0.259
p value	7	0.009	0.009
2 vs. 4			
Duopoly	6	0.322	0.464
Quadropoly	6	0.024	0.203
p value	6	0.014	0.014
3 vs. 4			
Triopoly	3	0.035	0.196
Quadropoly	3	0.049	0.174
p value	3	0.946	0.500

with regard to the different number of independent observations (treatments) for each number of competitors. Consequently, number effects are next investigated inter-study also via matched samples. By this means, a comparison of n_1 and n_2 competitors includes all studies that have conducted treatments with n_1 *and* n_2 competitors. Note that, therefore, the number of included studies varies between pairwise comparisons, e.g., when comparing two with four and two with three competitors. Table 5 presents average degrees of tacit collusion and p values based on one-tailed non-parametric Wilcoxon signed-rank tests. Again, the tested null hypothesis is that tacit collusion is higher in markets with more firms than in markets with less firms.

Test results show that tacit collusion is significantly higher in duopolies than in triopolies (2 vs. 3) and quadropolies (2 vs. 4), respectively. However, based on all experiments that run triopolies as well as quadropolies, the former is not more prone to tacit collusion than the latter (3 vs. 4). In fact, and in stark contrast to the existence of a strictly monotonic relationship, tacit collusion may even be slightly higher in markets with four firms ($\varphi^{Nash} = 0.049$) than in markets with three firms ($\varphi^{Nash} = 0.035$) and this difference is almost significant at the 5% level ($N = 3, p = 0.054$). Again, results are similar if tacit collusion metrics are averaged over all treatments of a study with the same competition model and two, three, or four firms, respectively (see Table F2 for results of corresponding Wilcoxon signed-rank tests).

2.4 Discussion of the meta-analysis

Based on the survey of the extant literature, there is no pooled evidence that would support a strictly monotonic relationship between the number of firms and the degree of tacit collusion in experimental oligopolies. Moreover, the studies that have examined number effects between three and four competitors within a single study likewise conclude that there is no significant difference between triopolies and quadropolies. For homogeneous Bertrand competition, both Dufwenberg and Gneezy (2000) and Davis (2009) find that experimental markets converge to the Nash equilibrium with three as well as with four competitors. For homogeneous Cournot competition, Huck et al. (2004) find more competitive output levels with four compared to three firms in absolute terms, however, this effect is reversed if the degree of tacit collusion is measured relative to the Nash equilibrium. Taken together, the results of the inter- and intra-study analyses are in line and suggest that the surveyed oligopoly experiments cannot confirm that markets with four firms exhibit, ceteris paribus, a lower degree of tacit collusion than markets with three firms. In conclusion, this contrasts the hypothesis of a strictly monotonic relationship between the number of competitors and the degree of tacit collusion.

Although meta-analyses can provide valuable insight by verifying robustness and external validity of systematic effects, they also have several limitations. First, the lack of control for all differences between studies considered in the same analysis limits the internal validity of meta-results. Second, in this specific meta-analysis the number of independent observations of the pairwise comparisons is rather low, which raises concerns about statistical power. In particular, only three studies cover both triopoly and quadropoly treatments.

Moreover, the individual studies themselves may lack statistical power to detect a difference between three and four competitors as the number of independent observations is often lower for markets with a larger number of competitors.[11] While all three studies are able to detect an effect between two and four firms with at least 60% statistical power, none of the studies could have detected an effect between three and four firms with a greater statistical power than 40%.[12] Third, both experiments that examine number effects in the context of price competition in a single study employ a homogeneous Bertrand model, which arguably represents a special case with regard to number effects, because the theoretical prediction is independent of the number of competitors. Last but foremost, none of the experiments in the meta-analysis employs treatments with all the relevant characteristics considered here, i.e., Bertrand and Cournot markets with two, three, and four firms.

3 Experiment with symmetric firms

Due to the lack of comprehensive evidence on a monotonic relationship between the number of firms and the degree of tacit collusion in the extant literature, we conduct our own oligopoly experiment based on a design that exploits the duality between Bertrand and Cournot competition. We begin by considering the case of symmetric firms, which is also assumed in all of the experiments surveyed in the meta-analysis. In the subsequent section, we will consider asymmetry between firms.

3.1 Experimental design

Price competition à la Bertrand and quantity competition à la Cournot serve as good proxies for a large share of models on oligopoly competition. As homogeneous price competition

[11] The three studies that examine triopolies and quadropolies (Dufwenberg and Gneezy, 2000; Huck et al., 2004; Davis, 2009) each base their analysis on six independent quadropoly observations.

[12] Statistical power is calculated based on the results of the experimental study in Section 3 and reported in Appendix D.

is often deemed unrealistic and yields a discontinuous demand function, we consider the model by Singh and Vives (1984) that generalizes the Hotelling (1929) model to exploit the duality between price and quantity competition in differentiated goods. More precisely, we use the model's generalization to more than two firms (see, e.g., Häckner, 2000). Whereas the details of the general case for asymmetric firms are relegated to Appendix A, we provide a sketch of the model for the case of symmetric firms here. Consider a market with $n \in \mathbb{N}$ firms. Each firm $i \in \{1, ..., n\}$ produces a single good. The firms' goods are differentiated horizontally, but are homogeneous in vertical quality and have identical demand elasticity, i.e., firms are assumed to be symmetric. For the Cournot treatments, the inverse demand for firm i is given by $p_i = \omega - \lambda \left(q_i + \theta \sum_{j \neq i} q_j \right)$ with $\omega, \lambda > 0$ and the degree of substitutability $\theta \in [-1, 1]$. For non-perfect substitutes ($\theta < 1$), the corresponding demand function for firm i in the Bertrand treatments is given by $q_i = \Omega - \Lambda p_i + \Theta \frac{\sum_{j \neq i} p_j}{n-1}$ with $\Omega = \frac{\omega}{\lambda(1+\theta(n-1))}$, $\Lambda = \frac{1+\theta(n-2)}{\lambda(1-\theta)(1+\theta(n-1))}$, $\Theta = \frac{\theta(n-1)}{\lambda(1-\theta)(1+\theta(n-1))}$, and n as the number of firms with non-negative demand, i.e., firms that have not exited the market due to a too high price. If $q_i < 0$ firm i exits the market, its quantity is set to zero, and n is decreased by one. Normalizing costs to zero, firm i's profit is $\Pi_i = p_i q_i$.

It is straightforward to show that $\Pi^{JPM} \geq \Pi^{Nash}_{Cournot} \geq \Pi^{Nash}_{Bertrand} \geq \Pi^{Walras}$ for all valid parameter combinations when goods are substitutes ($\theta > 0$). Then, also Nash prices are higher under Cournot competition than under Bertrand competition. In contrast, consumer surplus and total welfare in equilibrium are higher under Bertrand competition than under Cournot competition as both are monotonically decreasing in prices.

In the experiment, we ran treatments with Bertrand and Cournot competition in duopolies, triopolies, and quadropolies in a full-factorial design, resulting in a total of six treatments. In the following, these treatments are referred to with abbreviations such as B4 for the Bertrand quadropoly treatment. The model is parametrized with $\omega = 100$, $\lambda = 1$, and $\theta = \frac{2}{3}$. Consequently, $\Omega = \frac{300}{2n+1}$, $\Lambda = \frac{6n-3}{2n+1}$, and $\Theta = \frac{6n-6}{2n+1}$.

In line with the majority of the experiments considered in the meta-analysis, firms in our experiment interact repeatedly over several periods with the same firm.[13] In an effort to prevent that treatments evoke only short-term effects, the one-shot game is repeated 60 times. The fixed ending rule is announced to all participants prior to the experiment and thus the finite horizon of the experiment is common knowledge.[14] As in the surveyed experiments, perfect information is ensured in all treatments, i.e., subjects are provided with individual feedback about each competitor's price, quantity, and profit in each period.

Firms' incentives to tacitly collude are frequently studied in a repeated game context (see, e.g., Biancini and Ettinger, 2017; Ivaldi et al., 2003; Nocke and White, 2007; Normann, 2009). In finitely repeated games where the stage game exhibits a unique Nash equilibrium (which is the case there), the repeated game exhibits a unique subgame perfect Nash equilibrium that corresponds to the repeated play of the unique Nash equilibrium of the stage game (Benoit and Krishna, 1985; Suetens and Potters, 2007).[15] Thus, there is an extreme but testable theoretical prediction that in the present setting subjects should play the unique Nash equilibrium of the stage game in each period. The theoretical benchmarks of the one-shot game for each treatment are reported in Table F5 in the Appendix. As Nash prices, quantities, and profits do not coincide under Bertrand and Cournot competition and are additionally dependent on the number of competitors n, these variables are not adequate to compare tacit collusion across treatments. Thus, the same measure as for the meta-analysis is utilized, i.e., the degree of tacit collusion φ^E.

Moreover, Selten and Stoecker (1986), among others, argue that subjects' behavior in experiments with many periods, i.e., in long finitely repeated games, could be better

[13] In Dufwenberg and Gneezy (2000) firms play the same market setting repeatedly, but they are matched randomly in each period. Orzen (2008) considers both fixed matching and random matching of firms in separate treatments (see Table 1).

[14] With the single exception of Fonseca and Normann (2012), all the studies on number effects surveyed in Section 2 employ a fixed ending rule.

[15] Note that generally the equilibrium prediction for the finitely repeated (extensive form) game is less robust than for the one-shot (normal form) game (see, e.g., Kreps et al. (1982), Reny (1993) and Basu (1990)). We thank an anonymous reviewer for pointing this out.

explained by the theory of infinitely repeated games, although theoretically this would only apply to an experimental setting where there is a positive continuation probability after each period (which is not the case here). In an infinitely repeated game context additional subgame perfect Nash equilibria which may support prices above the equilibrium price of the stage game can be rationalized. In Appendix A.5, we therefore compare the critical discount factor $\delta = \frac{\pi^{Defect} - \pi^{JPM}}{\pi^{Defect} - \pi^{Nash}}$ (Friedman, 1971) across the treatments (see, e.g., Dijkstra et al., 2017, for a similar approach). This analysis supports the notion that tacit collusion is harder to sustain with more firms, and that this relationship is strictly monotonic, both for Bertrand and Cournot treatments.

In a further effort to maximize comparability between treatments and to prevent any source for behavioral effects other than the treatment, input and output variables in the experiment are scaled in the following way. The action space of prices in Bertrand treatments and quantities in Cournot treatments is equally set to $[0, 100]$ with a minimum increment of one and the JPM action at a price or quantity of 50. This ensures that the collusive action is not more or less behaviorally attractive across treatments and that the search costs of finding the collusive action are the same in all treatments. With the same intention profits are scaled so that they are equal in the Nash equilibrium. That is, a subject playing the Nash equilibrium of the one-shot game—given that its competitors play Nash as well—would make identical profits in all treatments.[16] Altogether, this precludes confounding effects of the experimental design and parametrization.[17]

Due to the normalization of input and output variables of the model, the different measures of the degree of tacit collusion have two desirable characteristics in our experiment.

[16]See, e.g., Huck et al. (2004) and Bosch-Domènech and Vriend (2003) for the same approach. Alternatively, profits may be standardized with respect to the collusive outcome. However, this would in turn lead to different Nash profits across treatments. Hence, firms would face diverse incentives to deviate from the theoretical Nash prediction.

[17]It is important to see that the scaling of prices, quantities and profits neither affects the magnitude of the collusion degree measure nor the critical discount factor in an infinitely repeated game context (see Appendix A.5). However, the scaling impacts the general payoff level for all subjects, which may have a behavioral effect on the degree of tacit collusion. We investigate a possible payoff effect in Appendix G.

Table 6: Nash predictions p^{Nash} and q^{Nash} as measured by the Walrasian-based degrees of tacit collusion φ^{Walras}.

	Bertrand	Cournot
Duopoly	0.50	0.75
Triopoly	0.33	0.60
Quadropoly	0.25	0.50

First, the Nash prediction-based degree φ^{Nash} serves as a good indicator of relative differences in tacit collusion between treatments as Nash equilibria vary with the competition model as well as with the number of firms in the market. Second, the Walrasian-based measure of tacit collusion φ^{Walras} assesses absolute differences to a uniform baseline, as the experiment is specifically designed to have a constant Walrasian equilibrium and collusive equilibrium across treatments. Due to the normalization of input variables, choosing a price or quantity of $p, q \in [0, 100]$ in the experiment directly translates to a Walrasian-based degree of tacit collusion of $2p\,\%$ in the Bertrand or $2(100-q)\,\%$ in the Cournot treatments, respectively. Consequently, as the equilibrium price level is monotonically decreasing with the number of firms, the Walrasian prediction associated with each treatment's Nash equilibrium is also monotonically decreasing as shown in Table 6. Therefore, if participants in the experiment behave in line with the Nash prediction and do not have an inexplicable preference towards a certain integer within the interval $[0, 100]$ or even choose prices and quantities randomly, we expect the Walrasian-based tacit collusion measure to decrease with the number of firms.

The consideration of the degree of tacit collusion based on the Walrasian equilibrium in our experiment is thus not only done for completeness, but also serves two additional purposes. First, the measure serves as a means to check whether subjects' behavior in the experiment is in line with decreasing Nash predictions for a larger number of firms. Although Nash-consistent behavior is also indicated by $\varphi^{Nash} = 0$ across markets with a varying number of firms, this equality is difficult to verify empirically as a non-significant difference may also result from a lack of statistical power. Precisely in this case, the Walrasian-based degree of tacit collusion should indeed decrease with the number of firms, and should thus differ significantly between markets with a varying number of firms. Second, in the model consumer surplus as well as total welfare are monotonically decreasing in prices if goods are substitutes and hence, for regulatory authorities, the Walrasian equilibrium may constitute an additional relevant theoretical benchmark.

3.2 Procedures

The experiment is computerized with *Brownie*, a *Java*-based experimental software (Hariharan et al., 2017). All sessions with symmetric firms were run at the Karlsruhe Institute of Technology in Karlsruhe, Germany in October 2014 (duopoly and triopoly sessions), April 2015 (quadropoly sessions), and May to July 2016 (additional quadropoly sessions). Disregarding the first period, in which subjects familiarized themselves with the experimental software and decided on their initial price or quantity, the sessions took roughly 30 minutes on average. Note that there are no practice periods, neither with, nor without interaction between subjects, and thus, no unobservable learning confounds occur. The matching of subjects is constant throughout a session (fixed partner matching). In total, 264 students of economic fields participated in the experiment. Subjects were recruited via the ORSEE platform (Greiner, 2015) until 2015 and via the hroot platform (Bock et al., 2014) from 2016 onwards and participated only in one of the treatments (between-subject design).

The protocol for each session follows five steps. First, upon entering the lab, subjects are randomly assigned to a chair, from which they can neither see nor speak to any other participant of the experiment. Second, after everyone has been seated, the experimental instructions are handed out to the participants in print and read aloud from a recording.[18]

[18] As an example, the experimental instructions for the B4 treatment together with a screenshot of the

The recording ensures that any confounding effect of the reader's voice, accent, or intonation is identical across sessions from the same treatment and as similar as possible across treatments. Therefore, identical paragraphs across treatments are recorded once and the recording is used in all treatments. Third, prior to the beginning of the experiment, each participant has to complete a computerized test of questions regarding the comprehension of the instructions. It is only allowed to proceed to the next question after the correct answer to the current question is entered. Fourth, after all subjects have successfully completed the test, the experiment starts automatically. Over the course of the experiment participants wear ear protectors so that they are not influenced by clicking noises of computer mouses or other noise disturbing noise. Fifth, following the end of the experiment, each participant is paid out the profits accumulated during the experiment privately and in cash. Following this protocol, the total length of a session from subjects' entering to leaving the lab was about one hour. The average payoff per subject was EUR 17.36.

3.3 Results with symmetric firms

The experimental data amounts to 12 Bertrand and Cournot duopolies and triopolies, each, as well as 16 (20) Bertrand (Cournot) quadropolies. Before analyzing the experimental data longitudinally, Figure 1[19] and Table 7 provide an overview of experimental data based on the level of independent cohorts over all 60 periods.[20]

For an in-depth analysis of firms' longitudinal behavior, we employ a mixed-effects model that controls for different base levels of tacit collusion in cohorts via a random intercept as well as for different time dependencies due to learning via a random slope.

experimental software are provided as supplementary material.

[19]Here, collusion degrees relative to the Nash equilibrium are displayed over all 60 periods. Figure F1 depicts an analogous figure for collusion degrees relative to the Walrasian equilibrium.

[20]Note that one duopoly in treatment C2 is exceptionally competitive. In particular, its average degree of tacit collusion based on Nash profits lies almost three standard deviations below the treatment mean. All results reported in the following also hold if this outlier is dropped.

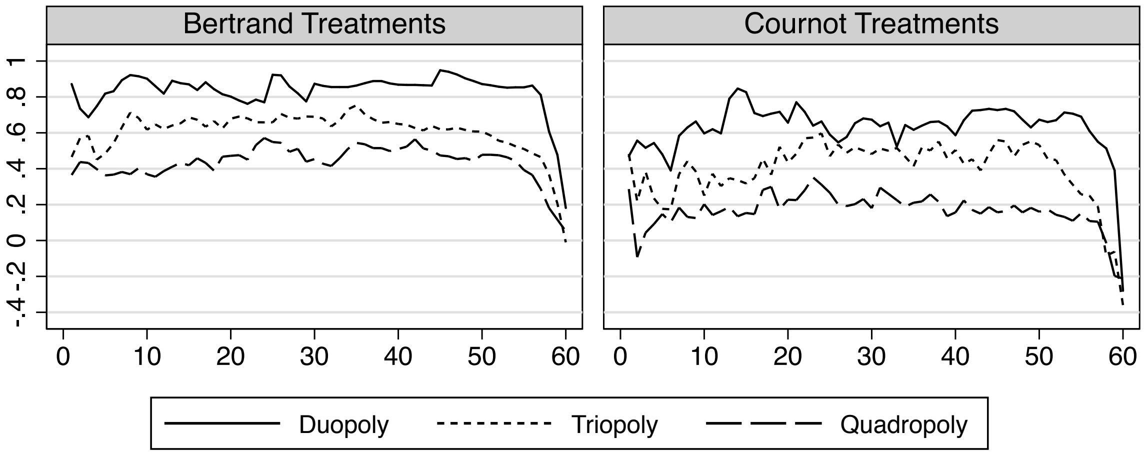

Figure 1: Average degree of tacit collusion φ^{Nash} over periods across treatments.

Thus, the estimated model is

$$\begin{aligned}\varphi^E_{k,t} = \beta_0 + \xi_k \\ &+ \beta_{Duopoly} \cdot Duopoly \\ &+ \beta_{Quadropoly} \cdot Quadropoly \\ &+ \beta_{Cournot} \cdot Cournot \\ &+ (\beta_{Period} + \beta_{Period,k}) \cdot t \\ &+ \epsilon_{k,t}\end{aligned}$$

with $\varphi^E_{k,t}$ as the average degree of tacit collusion of all firms' prices or quantities in cohort k in period t. Table 8 shows the estimated coefficients for both degrees of tacit collusion.[21] All results reported in the following with respect to prices or quantities hold also if the degree of tacit collusion is measured by transaction prices, i.e., prices weighted by the quantities sold. Moreover, the results are robust to different model specifications regarding the time trend (see Appendix E.1) as well as number-specific endgame effects (see Appendix E.2).

[21] Note that due to the dualism of the competition model used in the experiment, the degrees of tacit collusion measured by prices or quantities coincide.

Table 7: Average degrees of tacit collusion across treatments.

Treatment	N	φ^{Nash}	φ^{Walras}
B2	12	0.832	0.916
		(0.249)	(0.124)
B3	12	0.605	0.737
		(0.324)	(0.216)
B4	16	0.436	0.577
		(0.267)	(0.200)
C2	12	0.627	0.907
		(0.550)	(0.138)
C3	12	0.397	0.759
		(0.484)	(0.193)
C4	20	0.166	0.583
		(0.354)	(0.177)

Standard deviations in parentheses.

Result 2 *In the experiment with symmetric firms, the degree of tacit collusion based on the Nash or the Walrasian equilibrium is significantly higher in markets with two firms than in markets with three as well as four firms, and significantly higher in markets with three firms than in markets with four firms, everything else being equal.*

In line with the meta-analysis, the duopolies show, on average, a statistically significant 20 pp higher degree of tacit collusion than triopolies based on Nash predictions. Moreover, and in contrast to the meta-analysis, quadropolies show a statistically significant 23 pp lower degree of tacit collusion than triopolies. The similar effect sizes of both coefficients indicate not only a strictly monotonic, but a linear number effect in the degree of tacit collusion. According to a Wald test, the equality of the absolute value of treatment dummy coefficients cannot be rejected ($\chi^2(1) = 0.02, p = 0.888$). Measured relative to the Nash equilibrium, Bertrand competition colludes more than Cournot competition. In fact, the increase of 24 pp in the degree of tacit collusion is similar to the effect size found in the meta-analysis and also to the effect of an additional competitor in a market as reported above. Thus, with regard to number effects, the experiment replicates the findings of the

Table 8: Multilevel mixed-effects linear regressions of tacit collusion on number of competitors and competition model under competition between symmetric firms.

Covariate	(1) φ^{Nash}	(2) φ^{Walras}
Duopoly	0.204**	0.144***
	(0.092)	(0.045)
Quadropoly	−0.225***	−0.181***
	(0.083)	(0.041)
Cournot	−0.237***	−0.003
	(0.069)	(0.034)
Period	−0.001	−0.001
	(0.001)	(0.000)
Constant	0.676***	0.782***
	(0.073)	(0.036)
Cohorts	84	84
Observations	5,040	5,040

Baseline: Bertrand triopoly.
Standard errors in parentheses.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

meta-analysis with respect to duopolies and triopolies, but also identifies a significant effect between triopolies and quadropolies.[22]

With respect to the Walrasian-based degree of tacit collusion the data shows a significant 14 pp (18 pp) increase (decrease) in duopolies (quadropolies) compared to triopolies. Hence, there is also a monotonically decreasing, approximately linear trend of the degree of tacit collusion as the number of firms in the market increases. As discussed above, these findings indicate that subjects do indeed react to differences in theoretical predictions.[23]

In summary, the results attained from the experiment with symmetric firms provide support for the original conjecture of a strictly monotonic relationship between the number

[22]Note that these results also hold if the statistical analysis is limited to either Bertrand or Cournot competition (see Tables F6 and F7). The only exception is the difference between Cournot duopolies and Cournot triopolies, which is non-significant. However, this difference is rendered significant if a single, exceptionally competitive outlier from treatment C2 is dropped (see Table F8).

[23]These results also hold if only either Bertrand or Cournot competition is considered (see Tables F6 and F7).

of competitors and the degree of tacit collusion. In fact, the measured effect sizes point to a linear trend with regard to the degree of tacit collusion relative to the Nash equilibrium.

4 Experiment with asymmetric firms

As tacit collusion has been attributed to be driven by symmetry of firms in the economic literature (Mason et al., 1992; Ivaldi et al., 2003), number effects in oligopolies may also interact with the (a)symmetry of firms. Therefore, we consider two additional experimental treatments with asymmetric, i.e., vertically differentiated, firms. Thereby, we focus on the comparison of triopolies and quadropolies, which clearly is the most interesting case in light of our previous results.

Consideration of asymmetric firms also has a high practical relevance, particularly in the context of network industries, e.g., telecommunications and energy, which are often still characterized by a dominance of the former (state-owned) monopolist. In the following, we therefore conceive a market structure with one incumbent and two or three entrants competing against each other. This market structure also resembles the regularities of many European mobile telecommunications markets, which are comprised of one large and two or three smaller network operators, totaling at three or four cellular networks in each national market.

4.1 Experimental design and procedures

For means of comparability to the previous experimental treatments, the experimental design introduced in Subsection 3.1 is extended to allow for asymmetric firms. Asymmetry is implemented by establishing a single firm (i.e., the incumbent) with a higher quality good than the remaining—two or three—firms (i.e., the entrants). As consumers value quality, the incumbent's market share is higher than that of the entrants for identical prices. Equivalently, for equal market shares the incumbent may charge a higher price for its good than the entrants. In this vein, ω_i constitutes the reservation price of firm i's consumers in the model and thus, may be interpreted as the quality of firm i's product. Consequently, if the quality of one firm's product is higher than the quality of the other firms' products, i.e., $\omega_i > \omega_{-i}$, the former has higher market power that results in a higher equilibrium price, market share, and, with costs normalized to zero, profit. We refer to Appendix A for a thorough analysis of the model with horizontal as well as vertical differentiation. The extent of asymmetry in product quality can be expressed by a single parameter, $\Delta = \omega_{Incumbent} - \omega_{Entrant}$, which denotes the markup quality of the incumbent's good compared to the entrants' goods.

Two additional asymmetry treatments—an asymmetric Bertrand triopoly (B3A) and an asymmetric Bertrand quadropoly (B4A)—are considered. The parametrization for entrants is the same as for firms in the symmetry treatments, i.e., $\omega_{Entrant} = 100$, $\lambda = 1$, and $\theta = \frac{2}{3}$. Motivated by common market characteristics in oligopolistic industries with asymmetric market power, Δ however is now greater than zero and chosen such that the incumbent's Nash equilibrium profit is 50% higher than an entrant's Nash equilibrium profit. Thus, the incumbent's market share with regard to its proportion of joint Nash equilibrium profits is $^3/_7 \approx 43\%$ in a triopoly and $^1/_3 \approx 33\%$ in a quadropoly. As market power is a relative rather than an absolute concept, holding the relative profit markup of the incumbent constant has two important advantages over alternative approaches, such as holding the incumbent's market share constant. First, this allows to normalize entrants' equilibrium profits such that they are the same as in the symmetry treatments (see below), which increases comparability across the symmetry and asymmetry treatments. Second, the additional relative market power of the incumbent compared to any single entrant is independent of the number of firms which increases comparability between asymmetric triopolies and quadropolies. For the two asymmetric Bertrand treatments a Nash equilibrium profit markup for the incumbent of 50% corresponds to $\Delta = 6.10$ in triopolies and $\Delta = 4.79$ in quadropolies. The theoretical predictions of the one-shot game for both asymmetry treatments are listed in Table F9.

In order to further ensure comparability, the same scaling and normalization as in the previous experiment is applied: First, the action space of the incumbent is scaled such that the JPM prices of all firms coincide at a price of 50 in an action space of $[0, 100]$. Second, profits are standardized such that an entrant would have the same Nash equilibrium gains as a firm in any of the symmetry treatments. Consequently, incentives to deviate from the theoretical Nash prediction are equal for entrants and symmetric firms. The same scaling factor is applied to the entrants' as well as to the incumbent's profits so that the asymmetry in market power is not affected.

Except for an additional paragraph in the experimental instructions explaining how one of the firms differs from the others, the exact same experimental procedures are followed for the asymmetry treatments as previously for the symmetry treatments. Again, the experiment was run at the Karlsruhe Institute of Technology in Karlsruhe, Germany, and participants were recruited via the ORSEE platform for sessions between June and August 2015 and via the hroot platform for sessions in May 2016. None of the 104 students of economic fields participating in one of the two asymmetry treatments had previously participated in one of the symmetry treatments. The participants' payoff averaged at EUR 19.82.

4.2 Results

Similar to the symmetry treatments, there are 12 independent asymmetric Bertrand triopolies and 17 independent asymmetric Bertrand quadropolies. Summary statistics for both new treatments are provided in Table 9. Means over cohorts are computed by averaging over all firms, i.e., the incumbent and each entrant are weighted equally. Obviously,

Table 9: Average degrees of tacit collusion across asymmetry treatments.

Treatment	N	φ^{Nash}	φ^{Walras}
B3A	12	0.332	0.554
		(0.296)	(0.197)
B4A	17	0.217	0.412
		(0.148)	(0.111)

Standard deviations in parentheses.

this is not the only viable approach to aggregating firm-specific data on the cohort level. More generally, under asymmetry, JPM may not be the single natural benchmark to identify collusive behavior like under symmetry. Since our experimental study is focused on tacit agreements and thus does not allow for side payments between firms, JPM ensues that profits are shared according to firm-specific demand, i.e., relative market power. One might argue that this profit-sharing rule facilitates competition compared to, e.g., a uniform allocation of supra-competitive industry profits. However, such alternative benchmarks to JPM would exacerbate a comparison of asymmetric triopolies and quadropolies. The same holds for the comparison of our two studies with symmetric and asymmetric firms. Moreover, according to Bos and Harrington (2010), an allocation rule that ensures efficient production and lets firms keep their individual profits cannot only be derived theoretically from a notion of fairness, but is also empirically observable in numerous detected cartels. Thus, this profit-sharing rule is commonly used in the literature (Correia-da Silva et al., 2015). Finally, with respect to experimental analyses on tacit collusion, authors have investigated either simple average prices (see, e.g., Davis and Holt, 1994) or weighted average prices, i.e., transaction prices (see, e.g., Fonseca and Normann, 2008). In this vein, the following results are presented based on averages prices, but also hold if the degree of tacit collusion is measured by transaction prices, i.e., prices weighted by firm-specific production.

For an analysis of firms' behavior in the asymmetry treatments, we employ a similar mixed-effects model as for the symmetry treatments that controls for different base levels of tacit collusion in cohorts via a random intercept as well as for different time dependencies due to learning via a random slope. Thus, we estimate

$$
\begin{aligned}
\varphi^E_{k,t} = \beta_0 &+ \xi_k \\
&+ \beta_{Quadropoly} \cdot Quadropoly \\
&+ (\beta_{Period} + \beta_{Period,k}) \cdot t \\
&+ \epsilon_{k,t}
\end{aligned}
$$

with $\varphi^E_{k,t}$ as the average degree of tacit collusion of the incumbent's and the entrants' prices in cohort k in period t. Table 10 provides estimated coefficients for both measures of the degree of tacit collusion.

Result 3 *In the experiment with asymmetric firms, the degree of tacit collusion based on the Nash or the Walrasian equilibrium is significantly higher in markets with three firms than in markets with four firms, everything else being equal.*

The Nash-based degree of tacit collusion is, on average, 21 pp higher in triopolies than in quadropolies. In line with the previous findings from the symmetry treatments, this difference is statistically significant and similar with respect to the effect size. Also consistent with the results under symmetry, the Walrasian-based degree of tacit collusion is significantly higher in markets with three firms than markets with four firms. Furthermore, a negative time trend of prices due to an endgame effect can be found for both measures. These results hold if only the entrants' degree of tacit collusion is used.[24]

In summary, the empirical results under asymmetry replicate the findings under symmetry and thus support the general conjecture of a strictly monotonic relationship. Whereas

[24] If only the incumbent's degree of tacit collusion is considered the difference between triopolies and quadropolies is statistically significant for the Walrasian-based measure, but insignificant for the Nash-based measure.

Table 10: Multilevel mixed-effects linear regressions of tacit collusion on number of competitors under Bertrand competition between asymmetric firms.

Covariate	(1) φ^{Nash}	(2) φ^{Walras}
Quadropoly	-0.213^{*}	-0.203^{**}
	(0.120)	(0.081)
Period	-0.004^{***}	-0.002^{***}
	(0.001)	(0.001)
Constant	0.497^{***}	0.665^{***}
	(0.092)	(0.062)
Cohorts	29	29
Observations	1,740	1,740

Baseline: Bertrand triopoly.
Standard errors in parentheses.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

the relative effect on tacit collusion with regard to an additional competitor is similar across symmetric and asymmetric market structures, the absolute degree of tacit collusion for a market with a specific number of firms may differ, as a comparison of Tables 7 and 9 indicates.

While the detailed comparison of symmetry and asymmetry treatments is relegated to Appendix C, we briefly highlight that our experimental results indicate support for previous theoretical and empirical studies in their finding that symmetry facilitates tacit collusion (see, e.g., Mason et al., 1992; Ivaldi et al., 2003; Fonseca and Normann, 2008). In particular with regard to quadropolies, asymmetry is a significant driver of competition, with the degree of tacit collusion relative to the Nash (Walrasian) equilibrium being 18 pp (13 pp) lower in asymmetric than symmetric markets with four firms. Put into context, the effect size of implementing asymmetry in market power with a single firm exercising higher market power than its competitors is comparable to the number effect on tacit collusion from an additional competitor in the market.

In an effort to rule out social preferences—which may be viewed as an artifact of a laboratory setting—as a decisive motive for subjects' decisions to collude less under asymmetry, we measure their social value orientation in an ex post questionnaire based on Murphy et al. (2011). A comparison of the social value orientation index reveals no significant differences between incumbents and entrants or subjects in triopolies and quadropolies. In sum these findings suggest that social orientations cannot explain why asymmetric firms collude less than symmetric firms.

5 Conclusions

The question that motivates this work is rather blunt: *How many competitors are enough to ensure competition?* Evidently, it would be utterly unscientific to propose an answer to this question disregarding the particular characteristics and circumstances in a given market. But even if "case-by-case analysis implies that there is no 'magic number'" (Walle and Wambach, 2014, p. 10), the findings reported here point to systematic effects with regard to tacit collusion that should be given careful consideration by competition and regulatory authorities when assessing the question of how to achieve and safeguard effective competition in a market.

To this end, we provide comprehensive evidence from three independent studies based on either existing or new oligopoly experiments, considering a different number of firms (two vs. three vs. four firms), different modes of competition (price vs. quantity competition) and different distributions of market power (symmetric vs. asymmetric). The meta-analysis on the extant literature studying number effects in experimental oligopolies provides robust empirical support that tacit collusion is significantly higher in markets with two firms compared to markets with three firms as well as to markets with four firms, everything else being equal. However, neither intra-study nor inter-study evidence confirms a significant effect between markets with three firms and markets with four firms.

Thus, the extant literature does not provide any evidence for the original conjecture of a strictly monotonic relationship between the number of competitors and the degree of tacit collusion under Bertrand or Cournot competition. However, there are several limitations to the meta-analysis itself as well as the individual studies that compare markets with three and four firms. First, the data collected from experimental studies for the meta-analysis is heterogeneous in quality, i.e., it is either obtained from the authors directly, from online repositories, from tables in the article, or even retrieved from figures. As a consequence, the granularity of the data varies across studies. Data on the level of independent observations from sessions is only provided for half of the studies considered here and hence, intra-study treatment differences are neither replicable nor testable for the remaining studies. Second, the number of experimental studies surveyed in the meta-analysis is rather low, especially with regard to effects between triopolies and quadropolies, and thus the results are based on a small number of observations. Moreover, within the individual studies, the number of independent observations—in particular the number of independent quadropoly observations—is also rather low. In consequence, the meta-analysis as well as individual studies may simply lack the statistical power to detect a potential number effect between triopolies and quadropolies (cf. List et al., 2011; Bellemare et al., 2014).

Therefore, we conduct two own experiments that further test the relative competitiveness in triopolies and quadropolies based on a dataset with a considerably larger number of independent observations and an experimental design that exploits the duality between differentiated Bertrand and Cournot competition. As a result, we find a significant difference between markets with three firms and markets with four firms for both symmetric and asymmetric distributions of market power. Remarkably, the effect size of a 20-23 pp higher degree of tacit collusion is very similar from *four to three* firms as well as from *three to two* firms across symmetric and asymmetric treatments. This points not only to a strictly monotonic trend, but to a linear relationship between the number of firms and the degree of tacit collusion measured relative to the Nash equilibrium. Figure 2 summarizes these findings and depicts the number effect in prices/quantities across symmetric Bertrand and Cournot treatments.

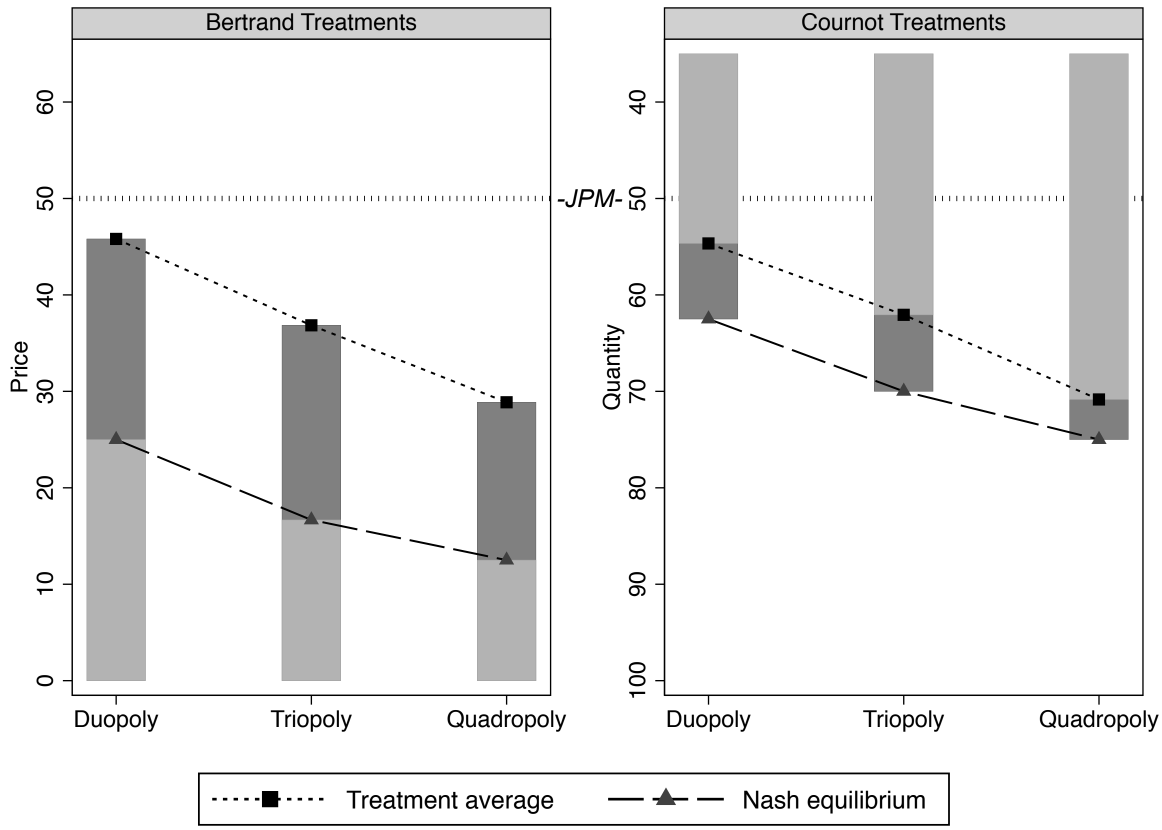

Figure 2: Number effects across symmetric treatments.

Furthermore, our results both confirm and shed new light on previous insights. First, our findings indicate that already the judgment of the competitiveness of a certain mode of competition (price vs. quantity competition) depends on the point of reference (Nash vs. Walrasian equilibrium). In particular, Suetens and Potters (2007) suggest that Bertrand colludes more than Cournot. However, as the empirical analysis reveals, this holds only with respect to the Nash equilibrium. Instead, the meta-analysis suggests that if tacit collusion is measured with regard to the Walrasian equilibrium, the opposite holds. This finding coincides with the stronger competition predicted by the Nash equilibrium under Bertrand competition than under Cournot competition. Second, the findings support the notion that tacit collusion is more likely to emerge among symmetric rather than asymmetric firms. Therefore, our results with respect to asymmetric firms based on differentiated price and quantity competition are in line with earlier experimental findings on differentiated Cournot competition (Mason et al., 1992; Mason and Phillips, 1997) and Bertrand-Edgeworth competition (Davis and Holt, 1994; Wilson, 1998; Fonseca and Normann, 2008), but contradict insights on homogeneous Bertrand competition (Argenton and Müller, 2012).

As pointed out by Davies and Olczak (2008), the theoretical and experimental findings that collusion is more likely with a low number of firms is at odds with the empirical observation that most prosecuted cartels involve five or more members. Following Garrod and Olczak (2018) this may be explained by a substitutive relationship between explicit and tacit collusion agreements: with a low number of firms tacit collusion is most successful, whereas with a high number of firms explicit collusion is. Our experimental results support this explanatory approach: First, tacit collusion becomes less sustainable with a higher number of firms. Second, there is still a significant level of tacit collusion with four firms, which is in line with the observation by Davies and Olczak (2008) that the median (average) number of cartel members in Europe is five (six).

Whereas our experimental studies address the limitations of the meta-analysis, they are at the same time limited to the specific parametrization used. This applies to both the specific demand parameters as well as to the way in which prices and profits are normalized and scaled across treatments in order to maximize comparability. Also the asymmetry between competitors may be parametrized in various ways, e.g., based on differences in Nash profits or based on absolute differences in product quality. Although there is considerable variation in parametrization across the studies included in the meta-analysis, it cannot be ruled out that the results of our own experimental studies are to some degree affected by the specific parametrization used.

As a further limitation of all studies it is noted that competition in experimental Bertrand and Cournot oligopolies is merely considered with exogenously symmetric or asymmetric firms, but not in the context of endogenous merger formation. Neither the experiments considered in the meta-analysis nor our own experiments allow for investments in product quality or market size, which are arguably vital parts of oligopolistic industries. Moreover, none of the experiments allowed for targeted punishments in markets with more than two firms. In other words, a deviation from a collusive agreement inevitably punishes all competitors in markets with more than two firms. Yet, Roux and Thöni (2015) find that the possibility to punish individual rivals facilitates tacit collusion in larger oligopolies. Finally, as in Huck et al. (2004) and Bosch-Domènech and Vriend (2003) we normalized equilibrium payoffs across treatments in order to be able isolate the impact of number effects on tacit collusion. However, thereby we implicitly neglected a possible payoff effect, because, e.g., in the case of a merger, equilibrium payoffs may in fact increase as the number of competitors decreases, while market size remains constant. In line with previous experimental research (Smith and Walker, 1993), we would expect that firms tend to collude less as payoffs increase, and indeed this is also what we find with respect to Bertrand triopolies (see Appendix G). Consequently, the payoff effect is likely to run opposite to the number effect, which we focus on here, with respect to its impact on tacit collusion.

These limitations give rise to future research on tacit collusion in oligopolies. In particular, the variety of asymmetric market settings offers opportunities for scenario-specific investigations of competitive effects. For instance, a decrease in the number of competitors in a market, e.g., through a merger, is also likely to affect the horizontal and vertical differentiation of firms' products. In this vein, a merger may introduce asymmetry in market power of the remaining firms and thus not only relax competition due to the decrease in the number of firms but also foster competition. Therefore, further experimental studies in the spirit of current replication efforts (see, e.g., Camerer et al., 2016) are desired to test the robustness and generality of the presented findings. Similarly, to date the payoff effect and its interaction with the number effect has not been studied systematically in experimental oligopolies. However, in reality, such as in mergers, both effects are present simultaneously. Finally, we note that there may also be an interaction of the number effect with the endgame effect in experimental oligopolies. Specifically, there is some indication that tacit collusion breaks down later in duopolies, relative to triopolies and quadropolies (see Figure 2 and Appendix E.2). However, our study was not designed to explicitly test for this interaction, and therefore, this remains an interesting area for future research.

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Appendix

A Oligopoly competition with asymmetric firms

Let the relevant industry consist of $n \in \mathbb{N}$ firms. Each firm produces one good and goods between firms are differentiated. Considering the representative consumer's utility function suggested by Singh and Vives (1984) and extending the generalization by Häckner (2000), inverse demand for firm $i \in \{1, ..., n\}$ is given by

$$p_i = \omega_i - \lambda_i q_i - \gamma \sum_{j \neq i} q_j$$

with $\omega_i, \lambda_i > 0, \forall i \in \{1, ..., n\}$ and the degree of substitutability γ. If $\gamma < 0$ goods are complementary, if $\gamma = 0$ goods are independent of one another, and if $\gamma > 0$ they are substitutes. ω_i may be interpreted as quality and thus, differences among firms as vertical differentiation. With substitute goods, ω_i is also firm i's reservation price. λ_i is the elasticity of inverse demand of firm i's good. For simplicity, assume that $\lambda_i = \lambda, \forall i \in \{1, ..., n\}$ and let $\theta = \frac{\gamma}{\lambda}$. This bounds $\theta \leq 1$ with goods being perfect substitutes if $\theta = 1$. The inverse demand for firm i then transforms to

$$p_i = \omega_i - \lambda \left(q_i + \theta \sum_{j \neq i} q_j \right). \tag{1}$$

Note that firms are vertically differentiated, i.e., asymmetric, and that symmetry requires $\omega_i = \omega, \forall i \in \{1, ..., n\}$. To calculate the demand for firm i, summarize Equation (1) over all n firms, which results in

$$\sum_{i=1}^{n} p_i = \sum_{i=1}^{n} \omega_i - \lambda \left(\sum_{i=1}^{n} q_i + \theta (n-1) \sum_{i=1}^{n} q_i \right)$$

using $\sum_{i=1}^{n} \sum_{j \neq i} q_j = (n-1) \sum_{i=1}^{n} q_i$. Solving this for $\sum_{i=1}^{n} q_i$ yields

$$\sum_{i=1}^{n} q_i = \frac{1}{\lambda(1+\theta(n-1))} \sum_{i=1}^{n} (\omega_i - p_i).$$

As a transformation of this equation, noting that

$$\begin{aligned} \sum_{i=1}^{n} q_i &= q_i + \sum_{j \neq i} q_j, \\ \sum_{i=1}^{n} \omega_i &= \omega_i + \sum_{j \neq i} \omega_j, \end{aligned} \tag{2}$$

and using Equation (1), firm i's demand for non-perfect substitutes ($\theta < 1$) is given by

$$q_i = \frac{(\omega_i - p_i)(1+\theta(n-2)) - \theta \sum_{j \neq i} (\omega_j - p_j)}{\lambda(1-\theta)(1+\theta(n-1))} \tag{3}$$

provided that the quantity is non-negative and with n as the number of firms with non-negative demand. Otherwise, if $q_i < 0$, firm i exits the market and its demand is zero.

With costs normalized to zero and $q_{-i} = \{q_1, ..., q_n\} \setminus q_i$, firm i's profit is given by $\Pi_i = p_i q_i$ with price $p_i(q_i, q_{-i})$ as a function of quantities in Cournot competition and quantity $q_i(p_i, p_{-i})$ as a function of prices in Bertrand competition. In the following analysis of Walrasian, Nash, and collusive equilibrium prices, quantities, and profits, subscripts are used to differentiate between Bertrand and Cournot competition.

A.1 Walrasian equilibrium

In the Walrasian equilibrium, also referred to as competitive equilibrium, firms are assumed to have no market power and hence, are price-takers with all prices at marginal cost. Therefore, the Walrasian equilibrium is identical under Bertrand and Cournot competition.

Setting Equation (1) to marginal cost, i.e., zero, it can be transformed to

$$q_i(q_{-i}) = \frac{\omega_i - \lambda\theta \sum_{j\neq i} q_j}{\lambda}.$$

Summing over all n firms gives

$$\sum_{i=1}^{n} q_i = \frac{\sum_{i=1}^{n} \omega_i - \lambda\theta(n-1) \sum_{i=1}^{n} q_i}{\lambda},$$

which, using the previous Equation together with Equation (2), yields the Walrasian equilibrium

$$\begin{aligned} q_i^{Walras} &= \frac{\omega_i(1+\theta(n-2)) - \theta \sum_{j\neq i} \omega_j}{\lambda(1-\theta)(1+\theta(n-1))}, \\ p_i^{Walras} &= 0, \\ \Pi_i^{Walras} &= 0. \end{aligned} \tag{4}$$

A.2 Nash equilibrium

In the Nash equilibrium under Cournot competition firm i maximizes Π_i with respect to its quantity q_i given the other firms' quantities q_{-i}. Firm i's best response is given by

$$q_i(q_{-i}) = \frac{\omega_i - \lambda\theta \sum_{j\neq i} q_j}{2\lambda}$$

and its sum over all n firms amounts to

$$\sum_{i=1}^{n} q_i = \frac{\sum_{i=1}^{n} \omega_i - \lambda\theta(n-1) \sum_{i=1}^{n} q_i}{2\lambda}.$$

Using the previous Equation together with Equation (2), the Cournot Nash equilibrium can be retrieved as

$$\begin{aligned} q^{Nash}_{Cournot,i} &= \frac{\omega_i(2+\theta(n-2)) - \theta\sum_{j\neq i}\omega_j}{\lambda(2-\theta)(2+\theta(n-1))}, \\ p^{Nash}_{Cournot,i} &= \frac{\omega_i(2+\theta(n-2)) - \theta\sum_{j\neq i}\omega_j}{(2-\theta)(2+\theta(n-1))}, \\ \Pi^{Nash}_{Cournot,i} &= \frac{(\omega_i(2+\theta(n-2)) - \theta\sum_{j\neq i}\omega_j)^2}{\lambda(2-\theta)^2(2+\theta(n-1))^2}. \end{aligned} \tag{5}$$

In the Nash equilibrium under Bertrand competition firm i maximizes Π_i with respect to its price p_i given the other firms' prices p_{-i}. Firm i's response function can be calculated as

$$p_i(p_{-i}) = \frac{\omega_i}{2} - \frac{\theta\sum_{j\neq i}(\omega_j - p_j)}{2(1+\theta(n-2))}.$$

Summing over all n firms yields

$$\sum_{i=1}^{n} p_i = \frac{\sum_{i=1}^{n}\omega_i}{2} - \frac{\theta(n-1)\sum_{i=1}^{n}(\omega_i - p_i)}{2(1+\theta(n-2))},$$

which can be transformed using the previous Equation together with Equation (2) to retrieve the Bertrand Nash equilibrium

$$\begin{aligned} q^{Nash}_{Bertrand,i} &= \frac{(1+\theta(n-2))(\omega_i(\theta^2(n^2-5n+5)+3\theta(n-2)+2) - \theta(1+\theta(n-2))\sum_{j\neq i}\omega_j)}{\lambda(1-\theta)(1+\theta(n-1))(2+\theta(n-3))(2+\theta(2n-3))}, \\ p^{Nash}_{Bertrand,i} &= \frac{\omega_i(\theta^2(n^2-5n+5)+3\theta(n-2)+2) - \theta(1+\theta(n-2))\sum_{j\neq i}\omega_j}{(1+\theta(n-1))(2+\theta(n-3))(2+\theta(2n-3))}, \\ \Pi^{Nash}_{Bertrand,i} &= \frac{(1+\theta(n-2))(\omega_i(\theta^2(n^2-5n+5)+3\theta(n-2)+2) - \theta(1+\theta(n-2))\sum_{j\neq i}\omega_j)^2}{\lambda(1-\theta)(1+\theta(n-1))^2(2+\theta(n-3))^2(2+\theta(2n-3))^2}. \end{aligned} \tag{6}$$

As Häckner (2000) shows, Nash prices are always higher under Cournot competition than under Bertrand competition for substitute goods ($\theta > 0$). Instead, if goods are complements ($\theta < 0$) and vertical differentiation between firms is high, Nash prices of low-quality firms may be higher under Bertrand competition than under Cournot competition. With respect to profits there are different nuances. For complementary goods, Nash profits are always higher under Bertrand competition than under Cournot competition. Instead, if goods are substitutes, the opposite holds unless vertical differentiation between firms is low, when Nash profits of high-quality firms may be higher under Bertrand competition than under Cournot competition.

A.3 Collusive equilibrium

In the collusive equilibrium firms employ JPM, i.e., firms behave like a single monopolist and maximize $\sum_{i=1}^{n} \Pi_i$. Therefore, the collusive equilibrium is identical under Bertrand and Cournot competition. Using Equation (1) and summing over the corresponding profit functions, joint profit of all n firms is given by

$$\sum_{i=1}^{n} \Pi_i = \sum_{i=1}^{n} (\omega_i q_i) - \lambda \sum_{i=1}^{n} q_i^2 - \lambda\theta \sum_{i=1}^{n} (q_i \sum_{j \neq i} q_j).$$

Noting that $\frac{\partial \sum_{i=1}^{n} (q_i \sum_{j \neq i} q_j)}{\partial q_i} = 2 \sum_{j \neq i} q_j$, the first-order condition of JPM can be calculated as

$$q_i(q_{-i}) = \frac{\omega_i - 2\lambda\theta \sum_{j \neq i} q_j}{2\lambda}.$$

Again summing over all n firms results in

$$\sum_{i=1}^{n} q_i = \frac{\sum_{i=1}^{n} \omega_i}{2\lambda} - \theta(n-1) \sum_{i=1}^{n} q_i,$$

which finally yields the collusive equilibrium using the previous Equation and Equation (2) as

$$
\begin{aligned}
q^{JPM} &= \frac{\omega_i(1+\theta(n-2)) - \theta \sum_{j\neq i} \omega_j}{2\lambda(1-\theta)(1+\theta(n-1))}, \\
p^{JPM} &= \frac{\omega_i}{2}, \\
\Pi^{JPM} &= \frac{\omega_i(\omega_i(1+\theta(n-2)) - \theta \sum_{j\neq i} \omega_j)}{4\lambda(1-\theta)(1+\theta(n-1))}.
\end{aligned} \tag{7}
$$

Note that JPM prices are linearly connected to vertical differentiation as firm i's price in collusive equilibrium depends solely on its own quality.

A.4 Symmetric firms

In case of symmetric firms without vertical product differentiation, i.e., $\omega_i = \omega, \forall i \in \{1, ..., N\}$, i's demand function, i.e., Equation (3), simplifies to

$$
\begin{aligned}
q_i &= \frac{(\omega - p_i)(1+\theta(n-2)) - \theta \sum_{j\neq i}(\omega - p_j)}{\lambda(1-\theta)(1+\theta(n-1))} \\
&= \underbrace{\frac{\omega}{\lambda(1+\theta(n-1))}}_{\Omega} - \underbrace{\frac{1+\theta(n-2)}{\lambda(1-\theta)(1+\theta(n-1))}}_{\Lambda} p_i + \underbrace{\frac{\theta(n-1)}{\lambda(1-\theta)(1+\theta(n-1))}}_{\Theta} \frac{\sum_{j\neq i} q_j}{n-1} \\
&= \Omega - \Lambda p_i + \Theta \frac{\sum_{j\neq i} q_j}{n-1}
\end{aligned}
$$

with $\Omega, \Lambda, \Theta > 0$ for substitute goods ($\theta > 0$). Consequently, the Walrasian equilibrium given by Equation (4), which predicts marginal cost pricing, simplifies to

$$
\begin{aligned}
q^{Walras} &= \frac{\omega}{\lambda(1+\theta(n-1))}, \\
p^{Walras} &= 0, \\
\Pi^{Walras} &= 0.
\end{aligned}
$$

In the Nash equilibrium under Cournot competition firm i maximizes Π_i with respect to q_i. With symmetric firms, Equation (5) yields the Cournot Nash equilibrium

$$\begin{aligned} q_{Cournot}^{Nash} &= \frac{\omega}{\lambda(2+\theta(n-1))}, \\ p_{Cournot}^{Nash} &= \frac{\omega}{2+\theta(n-1)}, \\ \Pi_{Cournot}^{Nash} &= \frac{\omega^2}{\lambda(2+\theta(n-1))^2}. \end{aligned}$$

In the Nash equilibrium under Bertrand competition firm i maximizes Π_i with respect to p_i. With symmetric firms and Equation (6), the Bertrand Nash equilibrium is given by

$$\begin{aligned} q_{Bertrand}^{Nash} &= \frac{\omega(1+\theta(n-2))}{\lambda(2+\theta(n-3))(1+\theta(n-1))}, \\ p_{Bertrand}^{Nash} &= \frac{\omega(1-\theta)}{2+\theta(n-3)}, \\ \Pi_{Bertrand}^{Nash} &= \frac{\omega^2(1-\theta)(1+\theta(n-2))}{\lambda(2+\theta(n-3))^2(1+\theta(n-1))}. \end{aligned}$$

Finally, in the collusive equilibrium, with firms employing JPM and irrespective of Bertrand or Cournot competition, Equation (7) simplifies to

$$\begin{aligned} q^{JPM} &= \frac{\omega}{2\lambda(1+\theta(n-1))}, \\ p^{JPM} &= \frac{\omega}{2}, \\ \Pi^{JPM} &= \frac{\omega^2}{4\lambda(1+\theta(n-1))}. \end{aligned}$$

A.5 Infinitely repeated game context

The incentives to tacitly collude in an infinitely repeated game can be analyzed by considering discounted gains from coordination relative to discounted gains from defection (see, e.g., Suetens and Potters, 2007, for an application in the context of oligopoly experiments). A collusive price configuration constitutes a Nash equilibrium in the repeated game if the loss due to punishment in future periods exceeds the one-time gain from defection. A typical punishment strategy to determine the Nash equilibrium is given by a grim trigger strategy, whereby a competitor punishes any deviation from the collusive state with an infinite play of the competitive Nash equilibrium (see, e.g., Normann, 2009).

Assuming that firms discount future profits with a common factor δ, the minimum critical discount factor that is required to sustain collusive outcomes in the context of a grim trigger strategy can be calculated as $\delta = \frac{\pi^{Defect} - \pi^{JPM}}{\pi^{Defect} - \pi^{Nash}}$, where π^{JPM} is the firm's share of the JPM profit, π^{Defect} is the maximum deviation profit that a firm can achieve by unilateral deviation, and π^{Nash} is the firm's profit in periods after deviation (cf. Normann, 2009). Collusion is sustainable for discount factors that exceed δ, and thus, a higher δ signifies that it is harder to sustain collusion. An alternative measure based on the same rationale is the *Friedman* index $F = \frac{\Pi^{JPM} - \Pi^{Nash}}{\Pi^{Defect} - \Pi^{JPM}}$ as suggested by Suetens and Potters (2007). A low critical discount factor δ corresponds to a high Friedman index F, and, consequently, a higher Friedman index indicates that collusion is more likely to be sustainable. Table A1 reports the respective profits π^{JPM}, π^{Defect} and π^{Nash}, together with the critical discount factor δ and the Friedman index F for all six treatments with symmetric firms. It can be seen that the critical discount factor increases, and the Friedman index decreases, as the number of firms in a market increase. This supports the notion that tacit collusion is harder to sustain with more firms, and that this relationship is strictly monotonic.

Table A1: Firms' profits and critical discount factors.

	Cournot					Bertrand				
	π^{JPM}	π^{Defect}	π^{Nash}	δ	F	π^{JPM}	π^{Defect}	π^{Nash}	δ	F
Duopoly	1500.00	1600.00	1406.25	0.52	0.94	1875.00	2500.00	1406.25	0.57	0.75
Triopoly	1674.11	1992.98	1406.25	0.54	0.84	2531.42	4556.25	1406.25	0.64	0.56
Quadropoly	1875.00	2500.00	1406.25	0.57	0.75	3214.29	7346.93	1406.25	0.70	0.44

B Meta-regressions of tacit collusion in oligopoly experiments that vary the number of competing firms

The use of multilevel regression models in meta-analyses has the shortcoming that the implicit weights associated to each observation, i.e., each treatment in a study, are of equal magnitude. However, each of these values stems from an experiment designed to predict a true effect. In other words, the averages of the degree of tacit collusion in each treatment of a study (i.e., the sample means) used in the analysis here are estimators of the true degree of tacit collusion (i.e., the population mean) in duopolies, triopolies, and quadropolies, respectively. Consequently, one might argue that the standard error of each sample mean should be considered as an indication of a sample mean's reliability. Meta-regression, a method vastly used in medical research (see, e.g., Higgins and Thompson, 2002), does exactly this by using the within-treatment standard errors as the standard deviations of the normal error terms in the model. More specifically, a random-effects meta-regression model is estimated which allows for between-study variance not explained by the covariates, i.e., the dummies for the number of firms.[25] This yields a weighted regression in which the inverse of the sum of the estimated between-study variance and the estimates' within-treatment variances are the individual weights associated to each treatment.

Table B1 depicts the estimates of meta-regression models with the same dependent and independent variables as in the multilevel mixed-effects regressions. Note that the number of observations in the meta-regressions is lower than in the corresponding mixed-effects models, because standard errors of treatment averages could not be gathered from all studies.[26] For this reason, the treatment Easy in Bosch-Domènech and Vriend (2003)

[25] The estimates reported in Table B1 are derived with the *metareg* command of the statistical software package *Stata* in its version 12. See Harbord and Higgins (2008) for further information on the command.

[26] The standard errors of the degree of tacit collusion estimates are derived with the following re-

Table B1: Meta-regression of tacit collusion on number of competitors and competition model on the basis of most comparable treatments.

Covariate	(1) φ^{Nash}	(2) φ^{Walras}
Duopoly	0.269***	0.308***
	(0.077)	(0.073)
Quadropoly	0.026	0.083
	(0.082)	(0.082)
Cournot	−0.182**	0.320***
	(0.076)	(0.067)
Constant	0.023	0.064
	(0.063)	(0.064)
Observations	21	21

Baseline: Bertrand triopoly.
Standard errors in parentheses.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

cannot be considered in the meta-regressions.

C Asymmetric market power and tacit collusion

Above and beyond number effects, we expect asymmetry to hinder coordination among firms as most of the economic literature suggests that symmetry is a driver of the ability to collude (see, e.g., Ivaldi et al., 2003; Fonseca and Normann, 2008). The hypothesis is thus that the degrees of tacit collusion based on Nash as well as Walrasian prices are significantly lower in markets with asymmetric firms than in markets with symmetric firms, everything else being equal.

Although there is only a single difference in the parametrization between each asymmetry treatment and its symmetry counterpart, the necessary adjustment of Δ according to

lationship: $SE\left(\varphi^E\right) = \frac{1}{\sqrt{N}}\sqrt{\frac{1}{N-1}\sum_{i=1}^{N}\left(\frac{p-p^E}{p^{JPM}-p^E} - \frac{\overline{p}-p^E}{p^{JPM}-p^E}\right)^2} = \frac{1}{\sqrt{N}}\sqrt{\frac{1}{N-1}\sum_{i=1}^{N}\left(\frac{p-\overline{p}}{p^{JPM}-p^E}\right)^2} = \frac{1}{p^{JPM}-p^E}\frac{1}{\sqrt{N}}\sqrt{\frac{1}{N-1}\sum_{i=1}^{N}\left(p-\overline{p}\right)^2} = \frac{1}{p^{JPM}-p^E}SE(p)$ with N as the number of independent observations for the corresponding treatment.

Table C1: Multilevel mixed-effects linear regressions of tacit collusion on (a)symmetry of firms in triopolies.

Covariate	(1) φ^{Nash}	(2) φ^{Walras}
Asymmetry	-0.185	-0.123
	(0.149)	(0.099)
Period	-0.004^{***}	-0.003^{***}
	(0.001)	(0.001)
Constant	0.685^{***}	0.790^{***}
	(0.106)	(0.070)
Cohorts	24	24
Observations	1,440	1,440

Baseline: Bertrand triopoly.
Standard errors in parentheses.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

the number of firms in the market impedes a simultaneous analysis of asymmetry and the number of firms. In other words, the treatment dummy between asymmetric triopolies and quadropolies is not the same as the one between symmetric triopolies and quadropolies. Therefore, in order to assess the effect of the specific type of asymmetry implemented here, i.e., providing a single firm with a 50% higher Nash profit than its competitors, requires separate investigations of triopolies and quadropolies.

Tables C1 and C2 depict estimates of multilevel mixed-effects linear regression models of tacit collusion on symmetry and asymmetry of firms whilst controlling for heteroscedasticity via a random intercept for the cohort and a random slope for the time trend, i.e.,

$$\begin{aligned}\varphi_{k,t}^{E} = \beta_0 + \xi_k \\ &+ \beta_{Asymmetry} \cdot Asymmetry \\ &+ (\beta_{Period} + \beta_{Period,k}) \cdot t \\ &+ \epsilon_{k,t},\end{aligned}$$

Table C2: Multilevel mixed-effects linear regressions of tacit collusion on (a)symmetry of firms in quadropolies.

Covariate	(1) φ^{Nash}	(2) φ^{Walras}
Asymmetry	-0.179^{**}	-0.135^{**}
	(0.075)	(0.056)
Period	-0.001	-0.001
	(0.001)	(0.001)
Constant	0.456^{***}	0.592^{***}
	(0.054)	(0.040)
Cohorts	33	33
Observations	1,980	1,980

Baseline: Bertrand triopoly.
Standard errors in parentheses.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

in triopolies and quadropolies, respectively. For maximum comparability, only the Bertrand treatments are included in the analysis for which there is data with both symmetric and asymmetric firms. In line with the hypothesis, the degree of tacit collusion is 18 pp (14 pp) lower in quadropolies with asymmetric compared to symmetric firms relative to the Nash (Walrasian) equilibrium. The degree of tacit collusion is not significantly lower with asymmetry in triopolies, although the average effect size of asymmetry is similar to the effect found for quadropolies. Given the lower number of observations this points to a lack of statistical power in the analysis of triopolies.

Prominent theories of fairness and equity in the behavioral sciences (e.g., Fehr and Schmidt, 1999; Bolton and Ockenfels, 2000) suggest that cooperation is harder to sustain in asymmetric than in symmetric games, which is in line with the finding here. In an effort to assess whether social preferences in fact account for the effect of asymmetry on tacit collusion, subjects' social value orientation is measured using the Murphy et al. (2011) questionnaire, which is completed by each participant subsequent to the oligopoly experiment at the end of a session, with the exception of one session with twelve participants in May 2016. Remember that incumbent firms are provided with higher market power than entrants in the asymmetry treatments. A comparison of the continuous social value orientation index reveals no significant differences between incumbents and entrants or subjects in triopolies and quadropolies. Among the four idealized social orientations of altruistic, prosocial, individualistic, and competitive behavior, the average participant is on the verge of prosocial and individualistic behavior. This finding is further corroborated in a categorical analysis which matches subjects to a single category. According to the classification, 46% of subjects are prosocials, 45% are individualists, and none are altruists or of competitive type—the remaining 9% cannot be assigned due to incomplete questionnaires. Again social orientations are not significantly different between subjects acting as firms of different types or participating in different treatments. Furthermore, social value orientations are not significantly correlated with the degree of tacit collusion. In sum, these findings suggest that participants' social orientations cannot explain why asymmetric firms collude less than symmetric firms.

The experimental evidence for quadropolies suggests that asymmetry fosters competition between firms in a market considerably and significantly. Put into context, the effect size of implementing asymmetry in a quadropoly by increasing the market power of a single firm is comparable to the number effect on tacit collusion.

D Statistical power analysis

Statistical power is calculated using the G*Power software (Faul et al., 2009). In order to estimate statistical power of the three studies that investigate markets with three and four firms, means and standard deviations obtained in our study with symmetric firms are used as approximations of the true population parameters (see Subsection 3.3). Calculations for Dufwenberg and Gneezy (2000) and Davis (2009) are based on Bertrand treatments of our study, whereas for Huck et al. (2004) only Cournot treatments are considered. Table D1 reports statistical power for pairwise treatment comparisons using one-tailed non-parametric Mann-Whitney U tests, which are employed in all three studies, given each study's number of observations per treatment N_n. Statistical power is calculated assuming a significance level of $\alpha = 0.1$.

Table D1: Statistical power of studies that investigate triopolies and quadropolies.

Study	N_2	N_3	N_4	2 vs. 4 firms	2 vs. 3 firms	3 vs. 4 firms
Dufwenberg and Gneezy (2000)	12	8	6	0.949	0.641	0.386
Davis (2009)	6	6	6	0.884	0.496	0.359
Huck et al. (2004)	6	6	6	0.630	0.287	0.344

N_n: number of observations per treatment with n firms.

E Time trend and endgame effect

E.1 Alternative model specifications

In order to test the robustness of our treatment effects for alternative specifications of a time trend, we first extend the mixed-effects model presented in Subsection 3.3 to control for a possible non-linear time trend by introducing a quadratic period coefficient as follows:

$$\begin{aligned}
\varphi^E_{k,t} = \beta_0 + \xi_k \\
&+ \beta_{Duopoly} \cdot Duopoly \\
&+ \beta_{Quadropoly} \cdot Quadropoly \\
&+ \beta_{Cournot} \cdot Cournot \\
&+ \beta_{PeriodSquare} \cdot t^2 + \beta_{Period} \cdot t \\
&+ \beta_{Period,k} \cdot t \\
&+ \epsilon_{k,t}
\end{aligned}$$

Table E1: Multilevel mixed-effects linear regressions of tacit collusion on number of competitors and competition model under competition between symmetric firms including a quadratic time trend.

Covariate	(1) φ^{Nash}	(2) φ^{Walras}
Duopoly	0.203**	0.144***
	(0.091)	(0.045)
Quadropoly	−0.225***	−0.181***
	(0.083)	(0.041)
Cournot	−0.237***	−0.003
	(0.069)	(0.034)
PeriodSquare	−0.000***	−0.000***
	(0.000)	(0.000)
Period	0.017***	0.009***
	(0.001)	(0.001)
Constant	0.490***	0.686***
	(0.073)	(0.036)
Cohorts	84	84
Observations	5,040	5,040

Baseline: Bertrand triopoly.
Standard errors in parentheses.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

The estimated coefficients presented in Table E1 indeed show that both the linear and the quadratic period coefficient are statistically significant, indicating a non-linear time trend. Yet, the treatment effects under this model specification are identical to the base model with regard to their respective effect sizes and their statistical significance.

Alternatively, Figure 1 suggests that the non-linear time trend may predominantly be driven by an endgame effect. To confirm this, we introduce a dummy variable *Last10Periods* that equals one for all periods $t \in [51, 60]$, and zero otherwise. We then estimate

$$\begin{aligned}
\varphi^E_{k,t} = &\beta_0 + \xi_k \\
&+ \beta_{Duopoly} \cdot Duopoly \\
&+ \beta_{Quadropoly} \cdot Quadropoly \\
&+ \beta_{Cournot} \cdot Cournot \\
&+ (\beta_{Period} + \beta_{Period,k}) \cdot t \\
&+ \beta_{Last10Periods} \cdot Last10Periods \\
&+ \epsilon_{k,t}.
\end{aligned}$$

The estimated coefficients presented in Table E2 confirm a statistically significant negative endgame effect in the last 10 periods. Moreover, controlling for the endgame effect captures enough variance in the linear time trend such that it becomes statistically significant as well. However, in terms of effect size, the linear time trend is still close to zero and similar as in Table 8. Again, the treatment effects are unaffected by this alternative model specification. Likewise, treatment effects are also robust in the experiment with asymmetric firms when a quadratic time trend or a dummy variable for the endgame effect in the last 10 periods is introduced.

E.2 Number-specific endgame effects

From the analysis in Section E.1, specifically Table E2, it is evident that there exists statistically significant and considerable endgame effect across all treatments. Moreover, Figure 1 and Figure F1 suggest that collusion degrees may be affected differently by such an endgame effect depending on the number of competitors in a market. In other words, the endgame effect may interact with the number effect.

Table E2: Multilevel mixed-effects linear regressions of tacit collusion on number of competitors and competition model under competition between symmetric firms including a dummy variable for the last 10 periods.

Covariate	(1) φ^{Nash}	(2) φ^{Walras}
Duopoly	0.203**	0.144***
	(0.091)	(0.045)
Quadropoly	−0.225***	−0.181***
	(0.083)	(0.041)
Cournot	−0.237***	−0.003
	(0.069)	(0.034)
Period	0.002**	0.001**
	(0.001)	(0.000)
Last10Periods	−0.216***	−0.112***
	(0.013)	(0.001)
Constant	0.620***	0.753***
	(0.073)	(0.036)
Cohorts	84	84
Observations	5,040	5,040

Baseline: Bertrand triopoly.
Standard errors in parentheses.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Generally, two effects may play a role in this context. First, since the endgame effect is triggered by the deviation (from a more or less collusive state) of any one firm in the oligopoly, there is, of course, a higher chance that the endgame effect is triggered earlier when the size of the oligopoly is larger. Following this argumentation, we should expect that the endgame effect first occurs in quadropolies, then in triopolies and then in the duopolies. Let us call this the *trembling hand effect*.

Second, in oligopolies with fewer firms, where tacit collusion levels are higher in a steady state (i.e., before the endgame effect commences), deviation profits are generally higher. This means that in duopolies the deviating firm is receiving a higher deviation profit than in triopolies, and so on. In the last few periods, the threat of subsequently lower profits does not adequately counterbalance this incentive to deviate anymore. Following this argumentation, we should expect that the endgame effect first occurs in duopolies, then in triopolies and last in quadropolies. Let us call this the *deviation profit effect*.

It is ultimately an empirical question, which of the two countervailing effects is stronger. In this context, we need to highlight that our experiment was not designed to address this question. Nevertheless, in the following we offer a first, cursory investigation towards this end that may be a fruitful starting point for future research.

Specifically, we introduce a dummy variable for each of the last ten periods (51-60) and add an interaction term for each of these periods with each oligopoly size to the regression model used in the main analysis (see Table E3). In this way, we can study, for each of the last 10 periods, whether for a given oligopoly size the endgame effect has already commenced (yielding a significant negative interaction effect for that period and oligopoly size) or not.

Based on the estimated coefficients denoted in Table E3 it can be seen that the endgame effect commences for duopolies in period 57 (interaction effects $DuopolyXPeriod$ are significant for all periods from 57 to 60). For triopolies, the endgame effect commences already in period 51, and in quadropolies the endgame effect commences in period 53 (52 when considering the Walrasian-based collusion measure). At the same time, notice that the treatment effects (*Duopoly*, *Quadropoly*, *Cournot*) are again robust and of similar effect size as in the main model specification.

In conclusion, this cursory evidence is in support of the conjecture that tacit collusion may be sustainable longer in duopolies than in triopolies or quadropolies. However, it also raises the interesting question whether this effect may be non-monotonic. In other words, it may be that the *trembling hand effect* and the *deviation profit effect* carry different weight in oligopolies of different sizes.

Table E3: Multilevel mixed-effects linear regressions of tacit collusion on number of competitors and competition model under competition between symmetric firms including number-specific endgame effects.

	(1)		(2)	
Covariate	φ^{Nash}	SE	φ^{Walras}	SE
Duopoly	0.238***	0.091	0.168***	0.045
Quadropoly	−0.190**	0.083	−0.169***	0.041
Cournot	−0.237***	0.069	−0.003	0.034
Period	0.002***	0.001	0.001***	0.000
Constant	0.581***	0.073	0.734***	0.036
DuopolyX50	−0.028	0.055	−0.011	0.027
DuopolyX51	−0.040	0.055	−0.015	0.028
DuopolyX52	−0.041	0.055	−0.017	0.028
DuopolyX53	−0.024	0.055	−0.013	0.028
DuopolyX54	−0.028	0.055	−0.014	0.028
DuopolyX55	−0.039	0.055	−0.017	0.028
DuopolyX56	−0.076	0.056	−0.025	0.028
DuopolyX57	−0.133**	0.056	−0.047*	0.028
DuopolyX58	−0.256***	0.056	−0.103***	0.028
DuopolyX59	−0.385***	0.056	−0.152***	0.028
DuopolyX60	−0.869***	0.056	−0.310***	0.028
TriopolyX50	−0.049	0.055	−0.030	0.027
TriopolyX51	−0.101*	0.055	−0.053*	0.028
TriopolyX52	−0.122**	0.055	−0.066**	0.028
TriopolyX53	−0.171***	0.055	−0.087***	0.028
TriopolyX54	−0.213***	0.055	−0.107***	0.028
TriopolyX55	−0.250***	0.055	−0.124***	0.028
TriopolyX56	−0.269***	0.056	−0.135***	0.028
TriopolyX57	−0.313***	0.056	−0.156***	0.028
TriopolyX58	−0.502***	0.056	−0.244***	0.028
TriopolyX59	−0.575***	0.056	−0.295***	0.028
TriopolyX60	−0.834***	0.056	−0.428***	0.028
QuadropolyX50	−0.058	0.045	−0.034	0.022
QuadropolyX51	−0.052	0.045	−0.031	0.022
QuadropolyX52	−0.072	0.045	−0.042*	0.023
QuadropolyX53	−0.086*	0.045	−0.050**	0.023
QuadropolyX54	−0.109**	0.045	−0.064***	0.023
QuadropolyX55	−0.110**	0.045	−0.071***	0.023
QuadropolyX56	−0.149***	0.045	−0.093***	0.023
QuadropolyX57	−0.187***	0.046	−0.121***	0.023
QuadropolyX58	−0.302***	0.046	−0.191***	0.023
QuadropolyX59	−0.435***	0.046	−0.265***	0.023
QuadropolyX60	−0.474***	0.046	−0.292***	0.023
Cohorts	84		84	
Observations	5,040		5,040	

Baseline: Bertrand triopoly.
SE: Standard error.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

F Supplementary tables and figures

Table F1: Multilevel mixed-effects linear regressions of tacit collusion on number of competitors and competition model on the basis of all treatments.

Covariate	(1) φ^{Nash}	(2) φ^{Walras}
Duopoly	0.208***	0.233***
	(0.037)	(0.030)
Quadropoly	−0.041	−0.009
	(0.046)	(0.037)
Cournot	−0.249***	0.316***
	(0.074)	(0.047)
Constant	0.077	0.138***
	(0.056)	(0.047)
Groups (s)	9	9
Groups (m)	10	10
Observations	23	23

Baseline: Bertrand triopoly. Standard errors in parentheses.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table F2: Inter-study average degrees of tacit collusion and one-tailed matched-samples Wilcoxon signed-rank tests on the basis of all treatments.

	Studies	φ^{Nash}	φ^{Walras}
2 vs. 3			
Duopoly	7	0.110	0.480
Triopoly	7	−0.079	0.260
p value	7	0.009	0.009
2 vs. 4			
Duopoly	6	0.302	0.452
Quadropoly	6	0.025	0.204
p value	6	0.014	0.014
3 vs. 4			
Triopoly	3	0.035	0.196
Quadropoly	3	0.049	0.174
p value	3	0.946	0.500

Table F3: Multilevel mixed-effects linear regressions of tacit collusion on number of competitors and competition model on the basis of most comparable fixed matching treatments.

Covariate	(1) φ^{Nash}	(2) φ^{Walras}
Duopoly	0.266***	0.269***
	(0.055)	(0.035)
Quadropoly	−0.029	−0.008
	(0.070)	(0.045)
Cournot	−0.230**	0.254***
	(0.097)	(0.052)
Constant	0.056	0.172***
	(0.078)	(0.055)
Studies	8	8
Models	9	9
Observations	20	20

Baseline: Bertrand triopoly.
Standard errors in parentheses.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table F4: Fixed effects regressions of tacit collusion on number of competitors on the basis of most comparable treatments with separate fixed effects for Betrand and Cournot treatments in Fouraker and Siegel (1963).

Covariate	(1) φ^{Nash}	(2) φ^{Walras}
Duopoly	0.254***	0.255***
	(0.053)	(0.035)
Quadropoly	−0.036	−0.014
	(0.067)	(0.044)
Constant	−0.021	0.250***
	(0.042)	(0.028)
Models	10	10
Observations	23	23

Baseline: Bertrand triopoly.
Standard errors in parentheses.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table F5: Scaled theoretical benchmarks of oligopoly competition for each treatment with symmetric firms as displayed in the experiment.

	Bertrand	Cournot
Duopoly	$p^{Walras} = 0$	$p^{Walras} = 0$
	$q^{Walras} = 60.00$	$q^{Walras} = 100.00$
	$\Pi^{Walras} = 0$	$\Pi^{Walras} = 0$
	$p^{Nash} = 25.00$	$p^{Nash} = 37.50$
	$q^{Nash} = 45.00$	$q^{Nash} = 62.50$
	$\Pi^{Nash} = 1406.25$	$\Pi^{Nash} = 1406.25$
	$p^{JPM} = 50.00$	$p^{JPM} = 50.00$
	$q^{JPM} = 30.00$	$q^{JPM} = 50.00$
	$\Pi^{JPM} = 1875.00$	$\Pi^{JPM} = 1500.00$
Triopoly	$p^{Walras} = 0$	$p^{Walras} = 0$
	$q^{Walras} = 42.86$	$q^{Walras} = 100.00$
	$\Pi^{Walras} = 0$	$\Pi^{Walras} = 0$
	$p^{Nash} = 16.67$	$p^{Nash} = 30.00$
	$q^{Nash} = 35.71$	$q^{Nash} = 70.00$
	$\Pi^{Nash} = 1406.25$	$\Pi^{Nash} = 1406.25$
	$p^{JPM} = 50.00$	$p^{JPM} = 50.00$
	$q^{JPM} = 21.43$	$q^{JPM} = 50.00$
	$\Pi^{JPM} = 2531.42$	$\Pi^{JPM} = 1674.22$
Quadropoly	$p^{Walras} = 0$	$p^{Walras} = 0$
	$q^{Walras} = 33.33$	$q^{Walras} = 100.00$
	$\Pi^{Walras} = 0$	$\Pi^{Walras} = 0$
	$p^{Nash} = 12.50$	$p^{Nash} = 25.00$
	$q^{Nash} = 29.17$	$q^{Nash} = 75.00$
	$\Pi^{Nash} = 1406.25$	$\Pi^{Nash} = 1406.25$
	$p^{JPM} = 50.00$	$p^{JPM} = 50.00$
	$q^{JPM} = 16.67$	$q^{JPM} = 50.00$
	$\Pi^{JPM} = 3214.29$	$\Pi^{JPM} = 1875.00$

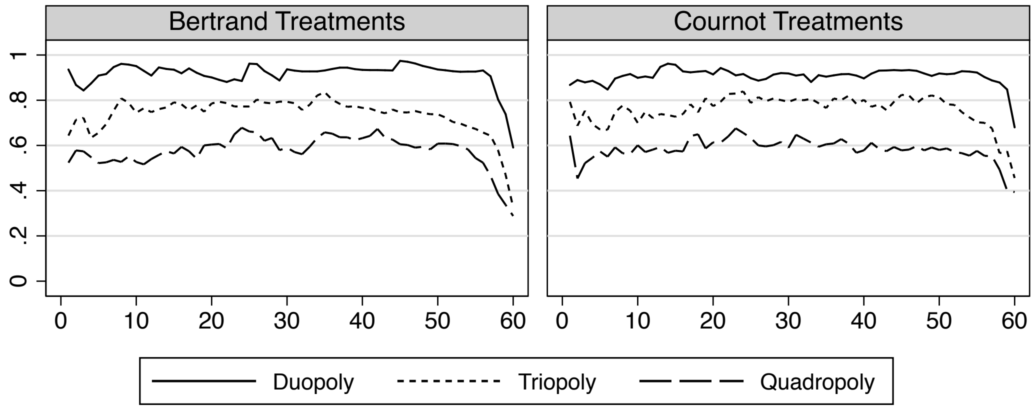

Figure F1: Average degrees of tacit collusion φ^{Walras} over periods across treatments.

Table F6: Multilevel mixed-effects linear regressions of tacit collusion on number of competitors under Bertrand competition between symmetric firms.

Covariate	(1) φ^{Nash}	(2) φ^{Walras}
Duopoly	0.190*	0.145**
	(0.102)	(0.067)
Quadropoly	−0.224**	−0.195***
	(0.095)	(0.063)
Period	−0.001	−0.001
	(0.001)	(0.001)
Constant	0.679***	0.786***
	(0.072)	(0.048)
Cohorts	40	40
Observations	2,400	2,400

Baseline: Bertrand triopoly.
Standard errors in parentheses.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table F7: Multilevel mixed-effects linear regressions of tacit collusion on number of competitors under Cournot competition between symmetric firms.

Covariate	(1) φ^{Nash}	(2) φ^{Walras}
Duopoly	0.217	0.140**
	(0.149)	(0.059)
Quadropoly	−0.226*	−0.170***
	(0.133)	(0.053)
Period	−0.001	−0.001
	(0.001)	(0.001)
Constant	0.435***	0.774***
	(0.105)	(0.042)
Cohorts	44	44
Observations	2,640	2,640

Baseline: Cournot triopoly.
Standard errors in parentheses.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table F8: Multilevel mixed-effects linear regressions of tacit collusion on number of competitors under Cournot competition between symmetric firms without C2 outlier.

Covariate	(1) φ^{Nash}	(2) φ^{Walras}
Duopoly	0.256*	0.149**
	(0.151)	(0.061)
Quadropoly	−0.226*	−0.170***
	(0.132)	(0.053)
Period	−0.000	−0.000
	(0.001)	(0.000)
Constant	0.432***	0.773***
	(0.105)	(0.042)
Cohorts	43	43
Observations	2,580	2,580

Baseline: Cournot triopoly.
Standard errors in parentheses.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table F9: Scaled theoretical benchmarks of oligopoly competition for the asymmetric Bertrand treatments as displayed in the experiment.

	Incumbent	Entrant
Triopoly	$p^{Walras} = 0$	$p^{Walras} = 0$
	$q^{Walras} = 55.92$	$q^{Walras} = 37.63$
	$\Pi^{Walras} = 0$	$\Pi^{Walras} = 0$
	$p^{Nash} = 18.26$	$p^{Nash} = 15.82$
	$q^{Nash} = 41.52$	$q^{Nash} = 33.90$
	$\Pi^{Nash} = 2109.38$	$\Pi^{Nash} = 1406.25$
	$p^{JPM} = 50.00$	$p^{JPM} = 50.00$
	$q^{JPM} = 27.96$	$q^{JPM} = 18.82$
	$\Pi^{JPM} = 4897.86$	$\Pi^{JPM} = 3166.26$
Quadropoly	$p^{Walras} = 0$	$p^{Walras} = 0$
	$q^{Walras} = 44.50$	$q^{Walras} = 30.14$
	$\Pi^{Walras} = 0$	$\Pi^{Walras} = 0$
	$p^{Nash} = 14.00$	$p^{Nash} = 11.98$
	$q^{Nash} = 34.23$	$q^{Nash} = 27.95$
	$\Pi^{Nash} = 2109.38$	$\Pi^{Nash} = 1406.25$
	$p^{JPM} = 50.00$	$p^{JPM} = 50.00$
	$q^{JPM} = 22.25$	$q^{JPM} = 15.07$
	$\Pi^{JPM} = 3889.00$	$\Pi^{JPM} = 2466.92$

Table F10: Nash predictions p^{Nash} as measured by Walrasian-based degree of tacit collusion φ^{Walras} under asymmetric Bertrand competition controlling for scaling in each treatment.

	Incumbent	Entrant
Triopoly	0.37	0.32
Quadropoly	0.28	0.24

G Payoff effects and tacit collusion

As described in Subsection 3.1, in our experiments with symmetric and asymmetric firms we scale profits such that firms' payoffs in the unique Nash equilibrium are identical across treatments. In doing so, we make a conscious design decision with respect to the inherent trade-off between internal validity and external validity (Plott, 1987). In particular, the normalization of equilibrium profits allows us to eliminate any additional and potentially confounding payoff effect on tacit collusion over and beyond the number effect, which is the focus of our study. Ensuring internal validity is then the foundation that enables us to make causal claims about the effect of the number of firms in a market on firms' propensity to tacitly collude. On the contrary, this design decision introduces limitations with regard to the external validity of our obtained experimental results. In the original (unscaled) oligopoly model of Singh and Vives (1984) and its generalization by Häckner (2000) the equilibrium payoff per firm increases as the number of firms in the market decreases. At the same time, a firm's profit in the JPM outcome will also increase as the number of firms in the market decreases. The payoff level may then have an additional effect on firms' propensity to collude over and beyond the number effect. For instance, if a merger reduces the number of firms in a market from four to three, each firm may be able to obtain higher profits, which could in turn dampen firms' "appetite for collusion".[27] Previous experimental studies in other contexts have found that behavior tends to approach the

[27] We thank an anonymous referee for pointing us to this issue.

theoretical (equilibrium) prediction when monetary rewards increase (Smith and Walker, 1993), and thus, we may expect that firms tend to collude less when payoffs increase. In theory, however, incentives for collusion should be unaffected by the payoff level and thus by scaling a firm's profit across treatments. To see this, consider the critical discount factor $\delta = \frac{\pi^{Defect} - \pi^{JPM}}{\pi^{Defect} - \pi^{Nash}}$ or the Friedman index $F = \frac{\Pi^{JPM} - \Pi^{Nash}}{\Pi^{Defect} - \Pi^{JPM}}$, which are both unaffected by a uniform scaling of firms' profit, as the equilibrium profit, and the JPM profit, and the defection profit are scaled by the same factor.

Design: To examine whether the level of firms' profits has an impact on firms' collusive behavior, we ran an additional Bertrand triopoly treatment (B3-NN) that employs the same scaling of profits as the Bertrand quadropoly treatment in Section 3, i.e., a triopoly treatment which is not normalized. Thus, profits in the triopoly treatment *without* normalization (B3-NN) are, ceteris paribus, higher than in the triopoly treatment with normalization (B3). Equilibrium profits and theoretical predictions of collusive behavior across both triopolies are summarized in Table G1.

Table G1: Firms' profits and critical discount factors in triopoly treatments.

Treatment	π^{JPM}	π^{Defect}	π^{Nash}	δ	F
Triopoly Normalized (B3)	2531.42	4556.25	1406.25	0.64	0.56
Triopoly Not Normalized (B3-NN)	4132.66	7438.77	2295.89	0.64	0.56

Procedures: The additional three sessions of the B3-NN treatment (with 18 participants each) were run at the Karlsruhe Institute of Technology in Karlsruhe, Germany in July 2017. The 54 students of economic fields were recruited via the hroot platform. None of them had previously participated in any of the symmetry or asymmetry treatments. The participants' average payoff amounted to EUR 33.19. In the experiment the exact same experimental procedures were followed and identical experimental instructions were used as in the B3 treatment.

Results: Summary statistics for both Bertrand triopoly treatments with symmetric firms are reported in Table G2.

Table G2: Average degrees of tacit collusion across treatments.

Treatment	N	φ^{Nash}	φ^{Walras}
B3	12	0.605	0.737
		(0.324)	(0.216)
B3-NN	18	0.484	0.656
		(0.297)	(0.198)

Standard deviations in parentheses.

In order to analyze the effect of profit scaling on tacit collusion, we employ a similar mixed-effects model as for the other treatments, controlling for different base levels of tacit collusion in cohorts via a random intercept and different time dependencies via a random slope. We estimate

$$\begin{aligned}\varphi^E_{k,t} = \beta_0 &+ \xi_k \\ &+ \beta_{HighPayoff} \cdot HighPayoff \\ &+ (\beta_{Period} + \beta_{Period,k}) \cdot t \\ &+ \epsilon_{k,t}\end{aligned}$$

with $\varphi^E_{k,t}$ as the average degree of tacit collusion of all firms' prices in cohort k in period t. Table G3 provides estimated coefficients for both measures of the degree of tacit collusion.

In the triopoly treatment where profits are not normalized (B3-NN), i.e., in a market where each firm makes a higher profit given the same prices and quantities, the Nash-based degree of tacit collusion is, on average, 23 pp lower than in the normalized triopoly treatment (B3). The Walrasian-based degree of tacit collusion is also significantly (15 pp) lower in the normalized triopoly treatment. Therefore, the payoff level is found to have a significant effect on firms' collusive behavior in markets with three firms that compete

Table G3: Multilevel mixed-effects linear regressions of tacit collusion on payoff level under Bertrand competition between symmetric triopolies.

Covariate	(1) φ^{Nash}	(2) φ^{Walras}
HighPayoff	-0.225^{**}	-0.150^{**}
	(0.090)	(0.060)
Period	-0.000	-0.000
	(0.001)	(0.001)
Constant	0.676^{***}	0.784^{***}
	(0.070)	(0.047)
Cohorts	30	30
Observations	1,800	1,800

Baseline: Bertrand triopoly.
Standard errors in parentheses.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

à la Bertrand. In turn, this supports our decision to normalize profits when we wish to isolate the ceteris paribus effect of the number of firms on tacit collusion. Whereas we can identify a significant payoff effect for Bertrand triopolies, an in-depth assessment of the level of profits on tacit collusion across markets with a varying number of firms and different modes of competition as well as possible interactions is beyond the scope of this paper. However, our results for a specific market scenario indicate that a systematic study of such payoff effects could provide meaningful insights about the effects of mergers on tacit collusion, where both a number effect, as identified in this study, *and* a payoff effect are present, the two of which have an opposing impact on tacit collusion.