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AUCTIONS WITH LEAKS ABOUT EARLY BIDS: ANALYSIS AND EXPERIMENTAL BEHAVIOR

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In sequential first- and second-price private value auctions, second movers are informed about the first movers' bid with commonly known probability. Equilibrium bidding in first-price auctions is mostly unaffected, but there are multiple equilibria in second-price auctions affecting comparative statics across price rules. We show experimentally that informational leaks in first-price auctions qualitatively confirm the theoretical predictions. In second-price auctions, we analyze and experimentally confirm the existence of focal equilibria, and provide evidence for individual consistency in equilibrium selection. (*JEL* D44, C72, C91)

I. INTRODUCTION

Most theoretical and experimental studies of sealed-bid auctions assume simultaneous bidding (Kagel 1995; Kaplan and Zamir 2014). Nonetheless, in government procurement or when selling a privately owned company (such as an NBA franchise), the auctioneer may approach bidders separately, the auction may be open for an extended period of time, or bidding firms/groups go through a protracted procedure of authorizing the bid—which may imply a sequential timing of decisions (cf. Bulow and Klemperer 2009). This provides an environment in which bids may leak to competitors who have yet to place a bid.[1]

Recent studies attempted to estimate the prevalence of such information leaks. Andreyanov, Davidson, and Korovkin (2018) identified leaks in Russian procurement auctions by assuming that the corrupt bidder who receives a leak—presumably via the auctioneer—bids near the closing of the auction after all the other bidders placed their bids, and the winning bid is close in value to the runner up. The data support the existence of widely prevalent leaks. Ivanov and Nesterov (2019) elaborated the analysis using machine learning methods to estimate that leaks occurred in 16% of over 600,000 auctions studied.

Our paper complements these studies by analyzing, theoretically and experimentally, situations in which bidding is sequential and information leaks about earlier bids are possible. Although the available field evidence is from first-price auctions (FPA), our analysis encompasses both first- and second-price auctions

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1. The auctioneer may also ask for an updated bid as, for example, in government procurement auctions where following initial bids, bidders are often requested to submit a *best and final bid*.

ABBREVIATIONS

CRRA: constant relative risk aversion
FM: first-mover
FPA: first-price auction
SM: second-mover
SPA: second-price auction

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(SPA). The analysis for second-price auctions extends to English, or ascending bid auctions, under the assumption that the bidding strategy is determined "in the office," before the bidding process commences. This predetermination renders the risk of leaks very relevant. In the field, the probability of a leak can be manipulated in various ways. Early movers can actively leak information; late movers can engage in industrial espionage or bribe the auctioneer, whereas sellers may try to prevent leaks through legal action or by imposing strict simultaneity of bids. As a first step in studying these environments, we assume exogenously given and commonly known leak probabilities and analyze the effects on bidding behavior and outcomes.

Several theoretical papers consider revisions of bids due to corruption. Menezes and Monteiro (2006) and Lengwiler and Wolfstetter (2010) assume that corrupt auctioneers offer the auction winner to revise their bid. Arozamena and Weinschelbaum (2009) analyze the effect of corruption on bidding in first-price auctions in an environment similar to ours under different value distributions. Our contribution to this literature is as follows. First, we extend the analysis of first-price auctions to risk-averse bidders and a continuum of leak probabilities, and provide experimental evidence supporting the theoretical analysis. Second, we analyze and characterize different equilibria in second-price auctions with leaks, and show experimentally that empirical bidding is consistent with three focal equilibria.

Our model considers independently and identically distributed private value auctions with two bidders and an exogenously given and commonly known probability of the first bid being leaked to the second bidder before her bidding. We derive how the equilibria of the first- and second-price sequential auction depend on leak probability and are affected by risk aversion. For first-price auctions, we extend the results of Arozamena and Weinschelbaum (2009) to show that for power function distributions of valuations—such as the uniform distribution—the unique equilibrium is invariant with leak probability for all CRRA utility functions. In this equilibrium, a second bidder who observes a first bid below her value wins the auction at the price equal to the first bid. Leaks, therefore, result in the second mover (SM) sometimes winning the auction in situation where the first bidder has a higher value and would have won if not for the leak. Furthermore, when the second mover's value is higher, the leak lowers the price she has to pay the seller. Consequently, an increase in leak probability increases the expected payoff of the second bidder while reducing that of the first bidder, the seller surplus and overall efficiency.

For second-price auctions, we show that multiple equilibria exist. These differ in the second bidder's strategy upon learning that the first bid exceeds her own value. In this case, a *rational loser* essentially sets the price for the first bidder, thus allocating the surplus between the first bidder and the seller.[2] While there is a continuum of rational loser bids, we distinguish three focal bids resulting in very different equilibria: (a) truthful bidding of the rational loser—equivalent to the value-bidding equilibrium of the simultaneous auction—in which the rational loser bids his value; (b) spiteful bidding in which the rational loser slightly underbids the first bid[3]; and (c) cooperative bidding, where the bid equals the reserve price of the seller.

The auction's outcome strongly depends on the selected equilibrium. With truthful bidding, leaked information is ignored, hence the leak has no effect on buyer surplus, seller revenue, or efficiency. In all other equilibria, efficiency decreases as the probability of a leak increases, with seller revenue and efficiency reaching a minimum in the cooperative equilibrium. Compared to truthful bidding (with or without leaks), the expected payoff for the first bidder is higher in the cooperative equilibrium and lower in the spiteful equilibrium, and vice versa for second bidders. These differences become more extreme as the probability of a leak increases.

Given these results, whether an auctioneer or a social planner should prefer the first- or second-price rule depends not only on equilibrium selection in the second-price auction but also, in some cases, on the probability of a leak. For example, efficiency under low leak probabilities is higher in all equilibria of the second-price auction compared to the equilibrium of the first-price auction. For high leak probabilities, however, it may be either higher or lower, depending on which equilibrium the bidders coordinate on. Thus,

2. We use the term *rational loser* to reflect that winning the auction would result in a negative payoff. It may still be rational to win the auction if the bidder enjoys a *joy of winning*. Joy of winning, however, does not provide a good description of behavior in experimental auctions (Levin, Peck, and Ivanov 2016).

3. Morgan, Steiglitz, and Reis (2003) proposed spite as a potential explanation for overbidding in second price auctions. Nishimura et al. (2011) and Kirchkamp and Mill (2019) provide experimental support for spite as a motive in auctions.

our results establish that possible espionage and leaks should be taken into consideration alongside other factors when designing an auction.[4]

We conducted an experiment to test actual human behavior in first- and second-price auctions with probabilistic leaks. In first-price auctions, the experiment provides a test bed for the qualitative theoretical predictions regarding the effects of leaks on bidding behavior, expected allocations, and efficiency. The results largely confirm the theoretical predictions. We find that first mover (FM) bids do not vary systematically with leak probabilities. Informed second bidders generally behaved rationally, winning the auction if and only if they can gain by doing so. Overall, leaks increase the second bidder's payoff and reduce the first bidder's payoff, seller revenue, and efficiency.

In second-price auctions, the experiment allows us to explore equilibrium selection with leaks. Empirically investigating equilibrium selection is important because ex ante it is not clear which equilibrium will be favored—as all equilibria have desirable features for certain bidders.[5] In the field, equilibrium selection is likely to be influenced by various factors, limiting the generalizability of our results—as it would any results, be it laboratory or field data. Nonetheless, we provide meaningful evidence that, even sans the sundry pressures existing in the field, people tend to follow the three focal equilibria outlined above in a fairly consistent manner. The three equilibria are able to organize most of the data, with different individuals gravitating towards different equilibria. Given the distribution of strategies in the experiment, higher leak probabilities were associated, on average, with lower efficiency while not affecting the surplus allocation in a systematic way. Comparing the two auction rules, we find that, without leaks, seller revenue is higher with the first-price rule as is often observed in experimental auctions (Kagel and Levin 2016). The revenue dominance of the first-price rules disappears, and possibly reverses as leak probability increases, providing illustrative evidence for the importance of incorporating leaks into auction design.

Our results contribute more broadly to several literatures. First, the sequential protocol has been studied, theoretically and experimentally, in the context of contests (Fonseca 2009; Hoffmann and Rota-Graziosi 2012; Segev and Sela 2014) and asymmetric bidders (Cohensius and Segev 2017). Although no previous study looked at the effect of equilibrium selection in second-price auctions with sequential moves, this topic has been indirectly addressed in ascending bid auctions. Cassady (1967) suggests, based on anecdotal evidence, that placing a high initial bid can deter other bidders from entry, which may be rational when participation or information acquisition is costly (Daniel and Hirshleifer 2018; Fishman 1988).[6]

Our study is also related to the literature on information revelation in auctions (Gershkov 2009; Kaplan 2012; Milgrom and Weber 1982; Persico 2000). Several papers study revelation of information about bidders' valuations by the auctioneer (Bergemann and Pesendorfer 2007; Eső and Szentes 2007; Kaplan and Zamir 2000; Landsberger et al. 2001). As in our study, Fang and Morris (2006) and Kim and Che (2004) compare first- and second-price mechanisms but focus on value revelation rather than on leaked bids. The predictions of Kim and Che (2004) were experimentally tested and corroborated by Andreoni, Che, and Kim (2007). The remainder of the paper is organized as follows. We describe and analyze the bidding contests in Section II. The experimental design is described in Section III, the findings are discussed in Section IV, and Section V concludes.

II. MODEL

Two bidders $i = 1, 2$, compete via bidding to buy a single indivisible good over two time periods. Each bidder i has private value v_i drawn independently from the continuous distribution F on [0, 1], with 0 denoting the exogenously given reservation price of the seller. At time 1 bidder 1, the first mover, submits an unconditional bid

4. For example, possible collusion is taken in the theoretical literature as a justification for using the first-price rule (Fehl and Güth 1987; Güth and Peleg 1996; Marshall and Marx 2007; Robinson 1985), though the experimental evidence is mixed (e.g., Hinloopen and Onderstal 2014; Hu, Offerman, and Onderstal 2011; Llorente-Saguer and Zultan 2017) for experimental evidence.

5. Truthful bidding is simple and frugal as well as ex-ante egalitarian. The cooperative equilibrium maximizes the bidders' joint surplus. The spiteful equilibrium is best, in expectation, for the second bidder—who arguably has the most influence on equilibrium selection.

6. See Avery (1998) for an analysis of jump bidding with affiliated values. See also Ariely, Ockenfels, and Roth (2005), Ockenfels and Roth (2006), and Roth and Ockenfels (2002) for an analysis of second-price auctions with endogenous timing.

$b_1(v_1)$. At time 2 bidder 2, the second mover, observes b_1 with probability p, and submits a conditional bid $b_2(b_1, v_2)$, and with the complementary probability $1 - p$ does not see b_1 and submits an unconditional bid $b_2(\emptyset, v_2)$. In case of a tie, it is assumed throughout that bidder 2 wins. The allocation and payments are determined either by the first-price auction (FPA) or second-price auction (SPA). We assume risk aversion, captured by utility function $u_i(v_i - \varpi_i)$ being concave and differentiable, and with ϖ_i denoting the price paid by the winner which is either b_i in the FPA or b_{-i} in the SPA. Losing pays $u(0) = 0$.

A. *First-Price Auction*

Our analysis extends Arozamena and Weinschelbaum (2009) to a continuous combination of a simultaneous and sequential bidding game and adding risk aversion. More specifically for the former, while in Arozamena and Weinschelbaum (2009) a leak occurs with certainty, in our case it occurs with probability $p \in [0, 1]$. Clearly, in the case of the FPA, a bidder, who is informed about his opponent's bid, will match the other bid when she can still gain from winning and will underbid when she cannot gain from winning. Given this strategy of the second bidder, we solve for the equilibrium strategies at time 1 in Proposition 1 (for the proof, see Appendix A.1).

PROPOSITION 1. *For F uniform and CRRA utility with symmetric Arrow-Pratt risk aversion parameter of r satisfying* $0 \le r < 1$, *the unique equilibrium bids are* $(b_1(v_1) = v_1/(2 - r)$; $b_2(\emptyset, v_2) = v_2/(2 - r))$.

The CRRA results mirror those of Cox, Smith, and Walker (1985, 1988). In equilibrium neither first nor conditional or unconditional second bids are affected by leak probability, but leaks can affect who wins and how much bidders earn (see Appendix A.2).

COROLLARY 1. *For F uniform, risk neutrality* ($r = 0$), *and the first-price auction, bidder* 1 *ex ante expects to earn* $\frac{1}{6} - \frac{p}{12}$, *and bidder* 2 *the amount* $\frac{1}{6} + \frac{p}{8}$. *Expected seller revenue is* $\frac{1}{3} - \frac{p}{12}$, *implying an efficiency loss of* $\frac{p}{24}$.

B. *Second-Price Auction*

The second-price auction has multiple equilibria in weakly undominated strategies when $p > 0$. While Arozamena and Weinschelbaum (2009) in the context of leaks in SPA only consider the equilibrium of truth-telling, we characterize all equilibria in weakly undominated strategies, and explore three focal ones in detail.[7]

When bidder 2 does not see 1's bid, it is weakly dominant to bid truthfully (Vickrey 1961):

$$b_2(\emptyset, v_2) = v_2 \text{ for all } v_2. \tag{1}$$

If bidder 2 observes that b_1 exceeds v_2, she will underbid b_1. We refer to such bidder 2 as a *rational loser* and denote the associated bid $b_2(b_1, v_2)$ by $g(b_1, v_2)$. To be rational, behavior is as follows.

PROPOSITION 2. $g(b_1, v_2) < b_1$ *for all* $v_2 < b_1$.

If bidder 2 observes $b_1 < v_2$, she will overbid b_1, with truthful bidding (v_2) being focal. Altogether the equilibrium bid of an informed bidder 2 is given by

$$b_2(b_1, v_2) = \begin{cases} v_2 & \text{if } b_1 \le v_2, \\ g(b_1, v_2) & \text{otherwise.} \end{cases} \tag{2}$$

Anticipating this, bidder 1 maximizes

$$p \int_0^{b_1} u(v_1 - g(b_1, v_2))dF(v_2) + (1 - p) \int_0^{b_1} u(v_1 - v_2)dF(v_2) + \int_{b_1}^1 u(0)dF(v_2),$$

where $u(\cdot)$ is bidder 1's differentiable and strictly increasing utility function.

If $g(b_1, v_2)$ is continuous, differentiable, and weakly increasing in both arguments, the first-order condition (valid for $b_1 \in [0, 1)$) is

$$p \cdot u(v_1 - g(b_1, b_1)) + (1 - p)u(v_1 - b_1) - u(0) = \frac{p}{F'(b_1)} \int_0^{b_1} u'(v_1 - g(b_1, v_2)) \times \frac{\partial g(b_1, v_2)}{\partial b_1} dF(v_2). \tag{3}$$

PROPOSITION 3. *If* $g(b_1, v_2)$ *is continuous, differentiable, and weakly increasing in both arguments, then any interior equilibrium strategy* $b_1(v_1)$ *must be consistent with* (3).

According to Proposition 3, multiple equilibria differ in $g(b_1, v_2)$, the conditional bid of a rational loser. In the following we distinguish

7. Even without leaks, second-price auctions have multiple equilibria, but in weakly dominated strategies, see for example Plum (1992) and Blume and Heidhues (2004).

TABLE 1
Equilibria and Expected Outcomes for F Uniform on [0, 1] and $r_1 = r_2 = 0$

Environment/Eqm.	$b_1(v_1)$	$g(b_1, v_2)$	Bidder 1	Bidder 2	Seller	Eff. Loss
First Price	$\frac{v_1}{2}$	·	$\frac{1}{6} - \frac{p}{12}$	$\frac{1}{6} + \frac{p}{8}$	$\frac{1}{3} - \frac{p}{12}$	$\frac{p}{24}$
SP-Truthful	v_1	v_2	$\frac{1}{6}$	$\frac{1}{6}$	$\frac{1}{3}$	0
SP-Spiteful	$\frac{v_1}{1+p}$	$\nearrow b_1$	$\frac{1}{6(1+p)}$	$\frac{1+3p(1+p)}{6(1+p)^2}$	$\frac{1+2p}{3(1+p)^2}$	$\frac{p^2}{6(1+p)^2}$
SP-Cooperative	$\frac{v_1}{1-p}$	0	$\frac{1+p+p^2}{6}$	$\frac{1-p}{6}$	$\frac{1-p^2}{3}$	$\frac{p^2}{6}$

three focal equilibria: in *SP-Truthful*, a rational loser bids her true value $g(b_1, v_2) = v_2$, in which case bidder 1 to also bid her value in equilibrium. In *SP-Spiteful*, a rational loser leaves as little for bidder 1 as possible by slightly underbidding him with $g(b_1, v_2) \nearrow b_1$, setting the price for bidder 1 at b_1, similar to first-price auctions. Accordingly, b_1 is lower in equilibrium for higher leak probabilities, and is higher for higher risk aversion. Finally, in *SP-Cooperative*, a rational loser favors bidder 1 and harms the seller by setting $g(b_1, v_2) = 0$. In this case, bidder 1 gains his full value in case of a leak, incentivizing him to increase his bid above his value as p increases, thereby improving the chance of exploiting a leak. By doing so, bidder 1 is exposed to negative profits if there is no leak, hence bids *decrease* with risk aversion. As p approaches 1, cooperative bidding has bidder 1 bidding equal to or above one (independent of v_2) and bidder 2 bidding zero. These intuitions are formalized in the following proposition (for the proof, see Appendix A.3).

PROPOSITION 4. *In the focal SPA equilibria, the bid of bidder* 1 *depends on* $g(b_1, v_2)$ *as follows*:

- *SP-Truthful*: $g(b_1, v_2) = v_2$ *and* $b_1(v_1) = v_1$.
- *SP-Spiteful*[8]: $g(b_1, v_2) = b_1$. *With risk neutrality, the bid* b_1 *solves* $v_1 = b_1 + p\frac{F(b_1)}{F'(b_1)}$, *in particular, for F uniform, we have* $b_1(v_1) = \frac{v_1}{1+p}$. *When u is concave, bidding is above that of risk neutrality.*
- *SP-Cooperative*: $g(b_1, v_2) = 0$. *With risk-neutrality, we have* $b_1(v_1) = \frac{v_1}{1-p}$ *for* $v_1 \le 1 - p$ *and* $b_1(v_1) \ge 1$ *otherwise. When u is concave, bidding is below that under risk neutrality.*

8. For the existence of a monotonic strategy by bidder 1 in SP-Spiteful, it is sufficient that the reverse hazard rate, $F'(v)/F(v)$, is decreasing.

Table 1 summarizes the ex ante expected first-mover and second-mover surplus, seller revenue, and efficiency in the FPA equilibrium and the three focal equilibria of the SPA for the uniform distribution and risk neutrality.[9]

Proposition 4 determines whether the equilibrium bid function is above or below the risk neutral solution. Under more restrictive preferences, it is possible to be more specific. The following remark illustrates the equilibria for CRRA preferences in SP-Spiteful, and for constant relative risk aversion (CARA) preferences in SP-Cooperative (where losses are possible and CRRA is therefore undefined). For details, see Appendix A.4.

REMARK 1. With risk aversion,

A. with SP-Spiteful and CRRA preferences it holds that $v_1 = b_1 + p \cdot (1 - r)\frac{F(b_1)}{F'(b_1)}$. When the reverse hazard rate is decreasing, bidding increases in r.

B. with SP-Cooperative and CARA preferences, bidding decreases in r.

While in our analysis the support of F is [0, 1], in the first price auction and SP-Spiteful a different support merely results in a shift of the equilibrium to that new support. For instance, in a first price auction with uniform distribution of valuations on [0,1], the equilibrium is to bid half one's value (under risk neutrality). If the distribution is uniform on [1,2], the equilibrium is to bid $\frac{v-1}{2} + 1$. With SP-Truthful and SP-Cooperative, the equilibrium is not shifted with the support.

While we have treated $g(b_1, v_2)$ as a representation of a pure strategy, it can also represent the expectation of a mixed strategy by bidder 2 or the expectation of several heterogeneous strategies used by different possible players. For instance, if fraction α play the strategy of *SP-Spiteful* and $1 - \alpha$ use *SP-Cooperative*—or any

9. See Appendix A.5 for calculations.

strategy where the expectation of bidder 2's strategy is $\alpha \cdot b_1$—then any equilibrium will have the first bidder behave as if bidder 2 is playing $g(b_1, v_2) = \alpha \cdot b_1$.

COROLLARY 2. *With risk neutrality, in all equilibria of SPA where the expected strategy of the second bidder obeys* (1) *and* (2) *with* $g(b_1, v_2) = \alpha \cdot b_1 + \beta \cdot v_2$ *(where* $\alpha, \beta \geq 0$ *and* $\alpha + \beta \leq 1$*), we have the first bidder choosing* b_1 *according to* $v_1 = (1 - p + (\alpha + \beta) \cdot p)b_1 + \alpha \cdot p \cdot \frac{F(b_1)}{F'(b_1)}$. *In the uniform case, bidder* 1*'s equilibrium strategy reduces to* $b_1(v_1) = \frac{v_1}{1-p+(2\alpha+\beta)p}$.

From Corollary 2, we see that in the uniform case $g(b_1, v_2)$ can be reduced to a linear function αb_1, where α incorporates the expected term $\mathbb{E}(\beta \cdot v_2) = \frac{\beta}{2}$. When $\alpha = 1/2$, bidding by bidder 1 is truthful. With increasing α or β, bidding by bidder 1 becomes less aggressive. This is true not only when F is uniform, but for general F (under a decreasing reverse hazard rate). This is true more generally when comparing equilibria. Suppose there are two equilibria, k and l, based on equilibrium strategies $g^k(b_1, v_2)$ and $b_1^k(v_1)$ for equilibrium k and $g^l(b_1, v_2)$ and $b_1^l(v_1)$ for l, then the following proposition holds:

PROPOSITION 5. *Under risk neutrality, if F is weakly concave and* $\frac{\partial g^k(b_1,v_2)}{\partial b_1} > \frac{\partial g^l(b_1,v_2)}{\partial b_1}$ *for all* $b_1 \geq 0, v_2 \geq 0$, *then* $b_1^k(v_1) < b_1^l(v_1)$ *for all* $v_1 > 0$.

Proof. The RHS of Equation (3) is (a) equal to 0 for $b_1 = 0$, (b) strictly increasing in b_1, and (c) strictly larger for g^k than for g^l. Thus, for a particular $v_1 > 0$, the b_1 that equates both sides for g^k is strictly smaller than for g^l. Hence, we have $b_1^k(v_1) < b_1^l(v_1)$ for all $v_1 > 0$. ■

Intuitively, Proposition 5 says that a more aggressive bidder 2 induces bidder 1 to bid less aggressively.

We close this section with two comments on the likelihood of leaks in view of the theoretical analysis. Namely, are bidders likely to initiate leaks, either leaking their own bids or attempting to discover another's bid? In FPA, leaks benefit the second mover, which provides incentives for espionage, either directly or by colluding with the auctioneer, as assumed in the Russian procurement auctions alluded to in the introduction. While there is no reason to expect that such leaks are confined to first-price auctions, no such comparable data are available for second-price auctions. There are, however, two theoretical arguments suggesting that leaks will occur in SPA. In this, we assume that a bidder can choose to leak or spy before the realization of her value, and that this decision is commonly known. Choosing to do so results in an exogenous probability p (which depends on the leak technology) of a leak.

First, some bidders may be known to have cooperative or spiteful inclinations towards other bidders,[10] which narrows down the equilibria to the cooperative or spiteful equilibrium, respectively. A spiteful second mover bidder whose type is commonly known can benefit from engaging in espionage, as the other bidder will respond by lowering her bid. Conversely, a bidder who knows the other bidder to be cooperative can benefit from leaking her own (inflated) bid, expecting the second mover to bid low.

A second argument follows a forwards induction type logic. By choosing to spy, the second mover signals her intention to coordinate on an equilibrium that will earn her more than she could get by not spying. Formally, we impose the two following conditions on the equilibria:

1. We only consider equilibria in non-weakly dominated strategies.
2. Players' beliefs assign a positive probability only to strategies that are part of some equilibrium.

Given condition 1, if the second mover chooses not to spy, bidders bid their value for an ex-ante expected payoff of $\frac{1}{6}$. This eliminates all leak-equilibria where the second mover obtains a lower payoff, and in particular the cooperative equilibrium. By condition 2, if the second mover chooses to spy, then the first mover makes a bid (that is part of an equilibrium) that implies an expected payoff of at least $\frac{1}{6}$ to the second mover. Spying now weakly dominates not spying.[11]

III. EXPERIMENTAL DESIGN

We ran six sessions, three for first-price and three for second-price auction. Each session included 32 student participants from universities in Jena, Germany, recruited using

10. Rational losers allocate the surplus between the auctioneer and the auction winner, reflecting specific inclinations towards one or both. For example, if the bidders are industry competitors, one may benefit from harming the other.

11. Related forwards induction notions such as the intuitive criterion (Cho and Kreps 1987) are not applicable because the second bidder's action as a rational loser does not affect her own payoff.

TABLE 2
Probability of Seeing Other's Bid

Treatment	Leak Probability (*p*)	Probability of Being Second Mover: Bidder *A*	Bidder *B*
Baseline	0	–	–
One-sided-1/4	1/4	0	1
One-sided-1/2	1/2	0	1
One-sided-3/4	3/4	0	1
Two-sym	1	1/2	1/2
Two-asym	1	1/4	3/4

Notes: The analyses reported in the paper are based on the baseline and one-sided treatments.

ORSEE (Greiner 2015). The experiment was programmed in z-Tree (Fischbacher 2007). At the beginning of the session, participants were randomly allocated to the roles of Bidder *A* or Bidder *B* and remained in these roles throughout the experiment. In each period, participants were matched in pairs of Bidder *A* and Bidder *B* within matching groups of eight.

The experiment included six treatments, varying in the probability that one bidder is informed of the other's bid before making a bid. In the *baseline* treatment, the probability of a leak was zero. In three *one-sided* treatments, Bidder *B* could discover Bidder *A*'s bid with probabilities of 1/4, 1/2, and 3/4, respectively. To this basic design we added two *two-sided* treatments. In the *two-sym* treatment, either Bidder *B* could observe Bidder *A*'s bid or vice versa, with equal probabilities. In *two-asym*, Bidder *B* could observe Bidder *A*'s bid with probability 3/4, and otherwise Bidder *A* could observe Bidder *B*'s bid. Table 2 summarizes the experimental treatments.

The two-sided treatments were not part of the main experiment, and were designed to test a secondary hypothesis, namely whether issues of procedural fairness affect equilibrium selection.[12] As the results rejected this hypothesis, we do not discuss it here further. Note also that, in contrast to the one-sided treatments, where participants participate in one auction either as a first or as a second mover, in the two-sided treatments participants simultaneously participate in two auctions, once as a first mover and once as a second mover. The results suggest that this difference in protocol affected behavior, precluding comparisons between the one-sided and two-sided treatments. Hence the results reported in this paper focus on the one-sided treatments. For full details, see Fischer et al. (2017).

The experiment included 36 periods arranged in 6 blocks of 6 periods, with 1 period for each of the 6 treatments in every block. The order of the treatments within each block was independently randomized for each matching group in the FPA sessions, and repeated for the SPA sessions to facilitate comparison across auction mechanisms.

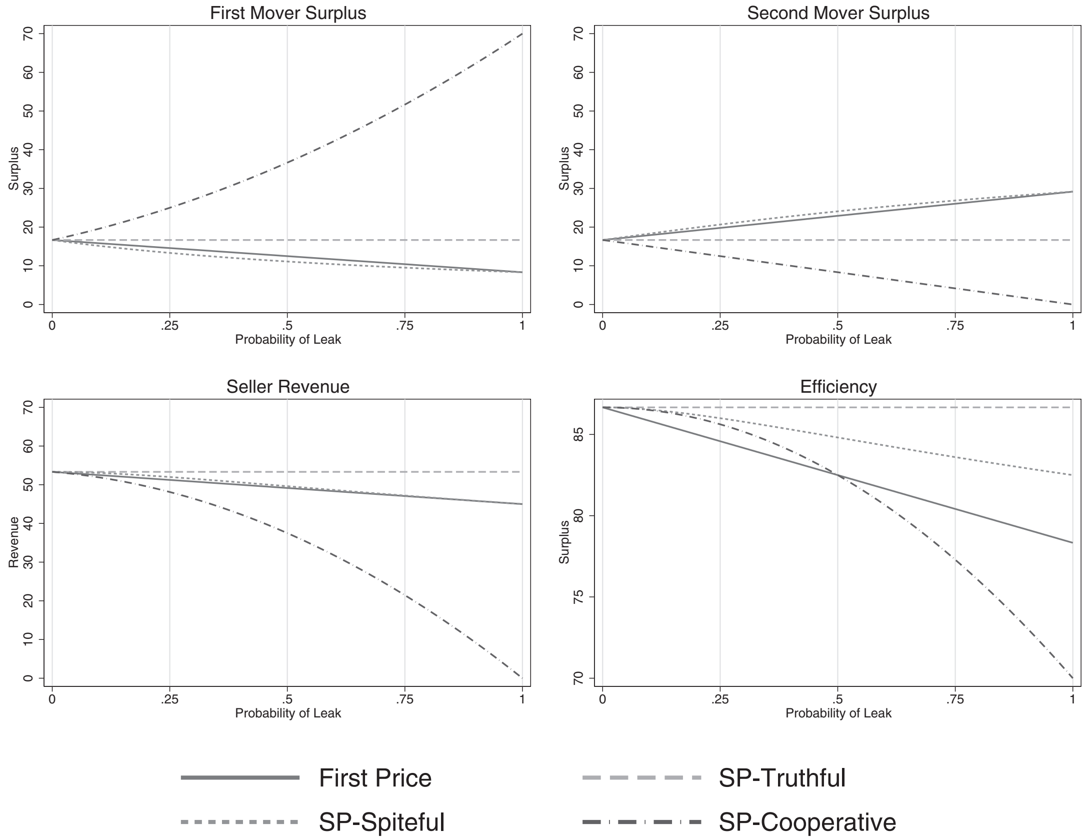
In each period, each bidder was assigned a privately known value drawn independently from the uniform distribution on [20.00,120.00] in steps of 0.01. All bids were restricted to be between 0.00 and 140.00 in steps of 0.01. Figure 1 plots the ex ante expected first-mover and second-mover surplus, seller revenue, and efficiency in the FPA equilibrium and the three focal equilibria of the SPA for the experimental parameters as a function of leak probability (cf. Table 1). Note that outcomes for FPA and SP-Spiteful are highly similar throughout.

We used the strategy method with respect to the realization of a leak as follows. The relevant leak probabilities were announced at the beginning of the period. Bidding then proceeded in two stages, corresponding to the unconditional and conditional bidding. First, both participants had to submit an *unconditional bid*. In all treatments other than the baseline, the potential second mover(s), was next (were) informed about the unconditional bid of the other bidder and submitted a *conditional bid*. Once all bids were placed, a random draw determined if there was a leak (and, in the two-sided treatments, in which direction). In case of a leak, the conditional bid of the second mover was used to determine the outcome of the auction. Note that using the conditional bid of one participant necessarily implies that the unconditional bid of the other participant was used. At the end of the period, participants received feedback about the outcome of the random draw (if applicable), the relevant bids, the winner of the auction and their own earnings for the period.

The instructions used nontechnical and unloaded terminology (see Appendix S2, Supporting information). We first explained the experimental game in play method, followed by a set of computerized control questions, to ascertain that participants understood the instructions. Once all participants successfully answered the control questions, we distributed a new set of instructions detailing the two-stage procedure. We randomly selected 5 of the 36 rounds for

12. We hypothesized that the highly unequal, yet efficient from the bidders' point of view, ex-post payoffs in SPA-Cooperative would be more acceptable if there is ex-ante symmetry (cf. Bolton, Brandts, and Ockenfels 2005; Krawczyk and Le Lec 2010).

FIGURE 1
Theoretical Predictions



payment. If the sum in these rounds was negative, they were subtracted from a show-up fee of €2.50 and an additional payment of €2.50 for answering the control questionnaire. Participants with any remaining negative balance would be required to work it off, however this never occurred.[13] Experimental currency unit payoffs were converted to money at the end of the experiment at a conversion rate of 1 ECU = €0.13 (approximately 0.177 USD). Sessions lasted between 85 and 135 minutes (including admission and payment) and the average payment was €15.41.

A. Experimental Hypotheses

Our main interest is in testing the predictions of the theoretical model and—in second-price auctions, where the model does not provide exact predictions—exploring behavior in view of the focal equilibria. The first three hypotheses are drawn directly from the theoretical analysis, and the fourth hypothesis touches on behavior in SPA in view of the equilibrium analysis.

Hypothesis 1 reflects optimality in the last stage of the game, as formalized in Equation (2).

Hypothesis 1. *Conditional bids* $b_i(b_j, v_i)$ *are optimal, that is,*

a. *in FPA,* $b_i(b_j, v_i) = b_j$ *if* $b_j \leq v_i$ *and* $b_i(b_j, v_i) < b_j$ *otherwise.*
b. *in SPA,* $b_i(b_j, v_i) \geq b_j$ *if* $b_j \leq v_i$ *and* $b_i(b_j, v_i) < b_j$ *otherwise.*

The next two hypotheses describe equilibrium strategies and outcomes in FPA. First, Proposition 1 implies that equilibrium unconditional bids b_1 and $b_2(\emptyset, v_2)$ are invariant to the leak probability in FPA.

13. For this purpose we had a special program prepared in which a participant would have to count the letter "t" in the German constitution, with each paragraph reducing the debt by €0.50.

Hypothesis 2. *In FPA, unconditional bids by first movers and second movers, $b_1(v_1)$ and $b_2(\emptyset, v_2)$, respectively, are unaffected by changes in leak-probability.*

The next hypothesis is drawn directly from the theoretical predictions summarized in Table 1 and Figure 1.

Hypothesis 3. *In FPA, the second-mover surplus increases and the first-mover surplus, seller revenue, and efficiency decrease with increasing leak probability.*

Moving to SPA, Proposition 5 implies that unconditional bids of first movers $b_1(v_1)$ in different equilibria may be below or above v_1, and that the deviation of the bid from the value increases with the leak probability. We therefore do not have specific predictions for SPA. Nonetheless, we hypothesize that bidders naturally use one of the three focal equilibria, Truthful, Spiteful, or Cooperative, and that there is intra-person consistency in rational loser strategies.

Hypothesis 4. *The three equilibria in SPA characterized in Proposition 4 are focal, that is,*

a. *Most rational-loser bids are consistent with one of the three equilibria.*
b. *Individual rational losers tend to bid consistently according to one of the three equilibria.*

Finally, the theoretical analysis has no clear predictions regarding aggregate outcomes (efficiency, revenue, and bidder surplus) in SPA, as these vary substantially depending on the selected equilibrium. In SP-Truthful, bids and aggregate outcomes are invariant to leaks. In other equilibria, leaks reduce efficiency and seller revenue, and either increase or decrease the first mover's surplus while having the opposite effect on the second mover's surplus. Accordingly, we do not state a formal hypothesis, but nonetheless aim to use our data to address the questions of how outcomes in SPA—and their comparison to FPA—vary with leak probability as an exploratory analysis.

IV. RESULTS

We first show that bidding strategies and aggregate outcomes—buyers' surplus, seller revenue, and efficiency—in FPA largely confirm the theoretical predictions stated in Hypotheses 1–3. We proceed to the more exploratory analysis of behavior and outcomes in SPA and conclude by commenting on the comparison between FPA and SPA. The analysis is restricted to the baseline and the one-sided treatments only.[14] When reporting results of mixed-effects regressions, these are based on maximum likelihood estimations of models of the general form

$$y_{git} = \mathbf{x}_{git}\beta + u_g + e_i + \epsilon_{git}$$

with $\mathbf{x}$ being the vector of regressors, g indicating the matching group, i the participant, and t the experimental round (period). Error term e_i is nested in u_g and all error terms, including ϵ, are assumed to be orthogonal to each other and the regressors. In other words, u_g and e_i are random group and individual effects, respectively. To control for potential learning effects in the first periods, we cross checked our results by running the same analysis once without the first observation of every treatment, and once excluding the first two repetitions. Unless mentioned otherwise, the results remain qualitatively unchanged. For ease of notation we will call role A and B bidders in the $p = 0$ treatments first-mover (FM) and second-mover (SM), respectively.

A. First-Price Auctions

Conditional Bids in FPA. We analyze the bidding behavior backwards, starting with conditional bids of informed second bidders. We categorize these bids into the five categories summarized in Table 3. The table reveals that bids are largely optimal. In 231 auctions the second mover could not profit from winning the auction, and indeed placed a winning bid in only one case. When the second mover could profit from winning, she did so in 619 of 633 (97.8%) of cases. Of these, 510 (82.4%) are optimal in the sense of extracting (almost) the maximal surplus by bidding no more than one unit above the first mover's bid. Winning bids above $b_1 + 1$ resulted in an average forgone gain of 16.8 ECU, or 31.5% of the maximum possible. Mixed-effects regressions of relative loss—defined as the forgone surplus divided by the maximum possible—on valuation, leak probability, and period reveal no significant effects for valuation ($\beta = -.001$, $p = .233$), leak probability ($\beta = -.107, p = .268$), or period ($\beta = -.001$, $p = .772$). Despite some suboptimality, the first part of Hypothesis 1 is therefore confirmed.

14. The two-sided treatments were not part of the main experiment and due to procedural differences cannot directly be compared with one-sided treatments. For full details, see Fischer et al. (2017).

TABLE 3
Conditional Bids in FPA

Category	Second Mover Can Gain $b_1 < v_2$	Second Mover Wins $b_2 \geq b_1$	Optimal	Proportion of Bids
Optimal loss	No	No	Yes	26.6%
Win at a loss	No	Yes	No	0.1%
Optimal win	Yes	Yes	Yes	59.0%
Non-optimal win	Yes	Yes	No	12.6%
Lose and forgo gains	Yes	No	No	1.6%

Notes: b_1 and b_2 are short for $b_1(v_1)$ and $b_2(b_1, v_2)$, respectively. An optimal win is defined as $b_1 \leq b_2 \leq b_1 + 1$ (to allow for rounding). Non-optimal win is defined as $b_1 + 1 < b_2 < v_2$.

RESULT 1. *Conditional bids in FPA are mostly optimal. Bidders rarely lose the auction when winning could have been profitable, or win the auction while losing money. Some bids do not extract the entire possible gain (independent of leak probability).*

Unconditional Bids in FPA. Table 4 presents mixed-effects regressions of the unconditional bids of first and second movers on the value (normalized to set the lower bound at zero) and leak probability, either as a continuous variable (columns 1 and 3) or as discrete treatments (columns 2 and 4).[15] From Proposition 1, if assuming risk neutrality the intercept should be 20 and the slope of v' equal to 0.5, irrespective of role and leak probability. The results in the first two columns show that for the first mover the constant is significantly lower than 20 ($\chi^2(1) = 34.92$ and $\chi^2(1) = 25.16$, respectively, $p < .001$) and the slope is highly significantly higher than 0.5 ($\chi^2(1) = 18.55$ and $\chi^2(1) = 16.86$, respectively, $p < .001$), which can be explained by risk aversion. As predicted, there is no significant effect for leak probability ($\chi^2(1) = 0.02$, $p = .884$ for continuous leak probability; $\chi^2(3) = 0.55$, $p = .909$ for the joint leak probability treatment effect).

The picture is somewhat different for second movers. The intercept is closer to the predicted 20 ($\chi^2(1) = 2.71$, $p = 0.100$ with continuous leak probability; $\chi^2(1) = 1.27$, $p = 0.260$ with leak probability treatments). The slope is still highly significantly higher than the 0.5 predicted for risk neutrality ($\chi^2(1) = 24.90$ and $\chi^2(1) = 18.51$ in columns 3 and 4, respectively). The main difference is that we see lower bids for higher leak probability ($\chi^2(1) = 3.68$, $p = 0.055$ for continuous leak probability; $\chi^2(3) = 7.45$, $p = 0.059$ for the joint leak probability treatment effect). We conjecture that when a bidder expects to have a chance to revise the current bid, she becomes less risk averse, pushing the bid towards the risk neutral Nash bid as the probability of revision goes up. Consistent with this interpretation, we find no significant difference in the mean bid between first and second mover for leak probability zero ($\Delta = 1.82$, $z = 1.46$, $p = 0.143$).[16] In fact, the difference is only significant for leak probability 3/4 ($\Delta = 7.59$, $z = 7.54$, $p < 0.001$), although the joint test across all four leak probability levels is not significant ($\chi^2(4) = 4.94$, $p = 0.294$).

RESULT 2. *Unconditional bids in FPA are mostly in line with Hypothesis 2, as the effects of leak probability are small and restricted to second movers.*

Aggregate Outcomes in FPA. Do the small deviations from equilibrium bidding affect the qualitative predictions for the auction outcomes, that is, bidders' surplus, seller's revenue and efficiency? Table 5 presents the key outcomes. As predicted, higher leak probabilities increase the probability that the second mover wins the auction, leading to a high expected payoff. As a result, the expected first mover's payoff and seller's revenue both decrease. As leaks favor the second mover even if the first mover's valuation is higher, they reduce efficiency.

Table 6 presents mixed-effects regressions confirming that the effects of leaks are significant. The only exception that does not reach significance is the reduction in the probability of an

15. To maintain comparability across treatments, here and in SPA we only consider Bidder *A*'s bids in the baseline treatment.

16. Based on a mixed-effects regression that includes the transformed value, dummies for leak probability treatments, role (first or second mover), and all two-way and three-way interactions. We do not report the full regression here due to space constraints.

TABLE 4
Unconditional Bids in FPA

	First Mover		Second Mover	
Constant	14.700***	14.911***	17.685***	18.070***
	(16.39)	(14.70)	(12.57)	(10.54)
v'	0.622***	0.633***	0.605***	0.606***
	(20.88)	(20.54)	(28.68)	(24.61)
pLeak	0.205		−5.118*	
	(0.15)		(−1.92)	
$v' \times$ probability	0.037		−0.093*	
	(0.98)		(−1.86)	
Leak probability 1/4		−0.190		−2.669
		(−0.22)		(−1.52)
Leak probability 1/2		−0.643		−2.183
		(−0.38)		(−1.19)
Leak probability 3/4		0.390		−4.421**
		(0.37)		(−2.14)
$v' \times 1/4$		−0.014		−0.024
		(−0.55)		(−0.77)
$v' \times 1/2$		0.001		−0.046
		(0.03)		(−1.19)
$v' \times 3/4$		0.024		−0.070*
		(0.72)		(−1.86)
N	1152	1152	1152	1152
χ^2	1749.0	3462.3	1601.2	9525.1

Notes: Linear mixed-effects regressions with random intercept effects on participant nested in effect on matching group. t statistics in parentheses based on Huber White sandwich estimation of standard errors $^*p < .1$; $^{**}p < .05$; $^{***}p < .01$. Transformed valuation $v' = v - 20$ used instead of v.

TABLE 5
Summary Table of Outcomes in FPA

Leak Probability	Prob (FM Wins)	FM Surplus	Prob (SM Wins)	SM Surplus	Revenue	Prob (High Value Wins)	Efficiency
$p = 0$	0.47	12.28	0.53	13.13	58.71	0.84	0.98
$p = 1/4$	0.46	12.13	0.54	17.50	56.57	0.83	0.97
$p = 1/2$	0.38	9.99	0.62	20.80	53.27	0.81	0.96
$p = 3/4$	0.39	8.95	0.61	20.59	52.67	0.78	0.95

Notes: Ex ante expected values given bidders' strategies and leak probability. Efficiency is defined as the winner's value divided by the highest value.

efficient outcome, however the effect of leaks on efficiency is highly significant. Hypothesis 3 is thus confirmed.

RESULT 3. *Leaks in first-price auctions increase the second mover's surplus, and decrease the first mover's surplus, seller's revenue and overall efficiency.*

B. *Second-Price Auctions*

Conditional Bids in SPA. Conditional bids in second-price auctions are mostly optimal. In 415 of 864 (48.0%) of the auctions, the first mover's bid was weakly below the second mover's value. In 393 (94.7%) of these, the second mover placed a winning bid. Eleven of the 22 auctions in which the second mover did not extract the possible gain, occurred in the first 8 of the 36 periods. Of the other 449 auctions in which the second mover could not make a profit, the second mover placed a losing bid in 443 (98.7%). With 97% of all conditional bids optimal, the second part of Hypothesis 1 is confirmed.

RESULT 4. *Conditional bids in SPA are mostly optimal. Bidders rarely lose the auction when winning could have been profitable, or win the auction while losing money.*

TABLE 6
Outcomes in FPA

	Prob(FM Wins)	FM Surplus	Prob(SM Wins)	SM Surplus
Constant	0.478***	13.829***	0.522***	14.478***
	(23.03)	(16.29)	(25.11)	(8.56)
Leak probability	−0.122***	−4.895***	0.122***	6.240**
	(−4.04)	(−3.56)	(4.04)	(1.98)
Period	−0.000	−0.063*	0.000	0.111
	(−0.38)	(−1.69)	(0.38)	(1.57)
N	1152	1152	1152	864
χ^2	17.3	15.1	17.3	5.5

	Revenue	Prob(High Value Wins)	Efficiency
Constant	56.411***	0.815***	0.969***
	(35.73)	(29.89)	(137.25)
Leak probability	−8.509***	−0.075	−0.033***
	(−7.80)	(−1.57)	(−3.94)
Period	0.113*	0.001***	0.001**
	(1.78)	(2.80)	(2.03)
N	1152	1152	1152
χ^2	62.0	10.3	18.8

Notes: Linear mixed-effects regressions with random intercept effects on participant nested in effect on matching group. t statistics in parentheses based on Huber White sandwich estimation of standard errors *$p < .1$; **$p < .05$; ***$p < .01$.

Our main analysis of SPA pertains to *Rational Losers*. In total, in 45.5% of all cases the informed second bidder had a lower valuation than the first bid ($v_2 < b_1$) and underbid in order to lose.[17] Table 7 presents a breakdown of conditional bids of rational losers according to the focal equilibria strategies. In total, 61.1% of bids fall into one of the three focal categories. That this is intentional coordination on the focal equilibria gains support from the comparison to FPA. In FPA, rational loser bids are not payoff relevant, hence their distribution provides a natural "null" distribution against which to compare the SPA bids. If it is the focal equilibria that drive rational loser bids in SPA, we should expect to see a different bid distribution in FPA. This is confirmed as in FPA the comparable share is 42.61%, mostly driven by 28.7% of rational losers in FPA who bid between 0 and 1. In particular, around one in four rational loser bid in SPA is spiteful, whereas no rational loser in FPA ever placed a bid within 1 ECU of the first bid.

Individual Types. Hypothesis 4b states that rational loser bids are consistent within individuals. We test this hypothesis by looking at the distribution of bid types, as categorized in Table 7.

17. This proportion is less than the 50% expected by chance if first bidders bid their value since, in contrast to the typical overbidding in second-price auctions, first bidders bid, for strategic reasons, on average less than their value.

TABLE 7
Rational Loser Bids

Category	Definition	Proportion of Bids
Cooperative	$g(b_1, v_2) \leq 1$	16.0%
Between cooperative and truthful	$1 < g(b_1, v_2) < v_2 - 1$	16.5%
Truthful	$v_2 - 1 \leq g(b_1, v_2) \leq v_2 + 1$	20.4%
Between truthful and spiteful	$v_2 + 1 < g(b_1, v_2) < b_1 - 1$	22.4%
Spiteful	$b_1 - 1 < g(b_1, v_2) < b_1$	24.7%

Notes: We categorize focal equilibria bids up to deviations of 1 ECU to allow for rounding, as many bidders places integer bids.

The number of times that a second mover in SPA was a rational loser varied from 4 (2 participants) to 12 (1 participant) periods, with an average of 8.2 and a standard deviation of 2.0. For every individual we measure consistency by calculating the share C of the most common category bid among all rational loser bids by that participant. For example, for a second mover who always made a *Cooperative* rational loser bid, $C = 1$, and for someone who made four rational loser bids of which three are *Spiteful* and one *Cooperative*, $C = 0.75$. In the first column of Table 8 we report the empirical share of second movers who always used the same category bid ($p(C = 1)$), the share who used their most

TABLE 8
Measures of Intra-Individual Consistency as Rational Losers

Statistic	Empirical	Simulation Mean	Simulation SD	Simulation Maximum
$p(C = 1)$	16.7%	0.1%	0.3%	6.3%
$p(C \geq 0.75)$	39.6%	1.2%	1.5%	12.3%
Mean(C)	0.69	0.40	0.01	0.48
Median(C)	0.71	0.39	0.02	0.48

Notes: C indicates the share of bids from the most frequent bid category (e.g., *Cooperative*) for a single individual, and $p(C)$ is the share of (simulated) participants with C. Simulation statistics based on 1,000,000 Monte-Carlo permutations.

common category bid at least 75% of the time ($p(C \geq 0.75)$), as well as the mean and the median of consistency measure C. To test the hypotheses that the distribution statistics on C reflect individual consistency, we ran Monte-Carlo permutation tests with 1 million repetitions, which are summarized in the remaining columns of Table 8.[18] For all four statistics, the empirical observation is well above the simulated distribution, providing strong evidence for intra-individual consistency beyond that expected by chance given the distribution of rational loser bids.

As an additional test of individual consistency, we regressed the relative conditional bids defined as conditional bids divided by the observed first bid ($\alpha_2 = [b_2(b_1, v_2) - 20]/(b_1 - 20)$, cf. Corollary 2), on a constant with fixed participant effects, resulting in an adjusted $R^2 = 0.508$. Thus much of the variation in the data is due to type heterogeneity. On average, the relative conditional bid is 0.51. Note that, by Corollary 2, this implies that risk neutral first movers should bid (approximately) truthfully.

To complete the picture, we analyze individual types by categorizing participants based on the mean absolute deviation from the focal equilibrium bids. We find that 41.67% of individuals bid closest to truthful, 37.50% bid closest to spiteful, and 20.83% bid closest to cooperative. Overall, the median absolute deviation from the closest focal bid is 1.30, and the median of the average absolute deviation for each individual given her type is 12.05.[19]

RESULT 5. *The three focal equilibria in SPA—Cooperative, Truthful, and Spiteful—account for most rational loser bids. Furthermore, individuals tend to bid consistently (although not exclusively) in line with one of the focal equilibria, confirming Hypothesis* 4.

Unconditional Bids in SPA. Table A in Appendix S1 presents mixed-effects regressions of the unconditional bids of first and second movers on the value (normalized to set the lower bound at zero) and leak probability (cf. Table 4). The estimated bid functions do not deviate significantly from truthful bidding, that is, a constant of 20 and a slope of 1 on the transformed value. These bidding strategies are roughly consistent with money maximizing.[20]

Aggregate Outcomes in SPA. Unconditional bids are, on average, close to truthful bidding, and in the absence of systematic deviations we expect the aggregate outcomes not to vary, on average, with leak probabilities. Mixed-effects regressions of the different outcomes measures on leak probability confirm this result (see Table C in Appendix S1 for details).

RESULT 6. *Leaks in second-price auctions have nonsignificant and mostly inconsistent effects on bidders' surplus, seller's revenue, and efficiency.*

Comparison of Auction Mechanisms. We conclude the analysis with an exploratory comparison of outcomes between FPA and SPA. Table 9 reports the marginal effects of the second-price mechanism over the first-price mechanism on bidders' surplus, seller's revenue, and efficiency based on mixed-effects regressions of the outcome on mechanism interacted with treatment and period.[21] The results in the baseline treatment ($p = 0$) match the existing experimental auctions, namely overbidding in FPA leads to higher seller revenue and lower bidders' surplus. Overbidding in FPA is independent of the leak probability. With leaks, however, an additional effect

18. These tests generate the null distribution given the empirical distribution of bid categories and the empirical distribution of number of rational loser bids per bidder.

19. For comparison, we repeated this analysis on simulated bids, by replacing every conditional bid $b_2(b_1, v_2)$ for $v_2 < b_1$ with a random draw from the uniform distribution $[0, b_1]$. The results of 10,000 such simulations yielded an average median deviation of conditional bids from the closest type of 21.61 (SD 1.15) and an average median deviation from the individual type (based on the simulated bids) of 26.25 (SD 1.17).

20. For second movers bidding truthfully is weakly dominant. For first movers, it is best response to the empirical rational loser behavior (cf. Corollary 2 and the analysis of relative conditional bids above).

21. See also the aggregate outcomes in SPA reported in Table B in Appendix S1.

TABLE 9
Differences in Outcomes in SPA over FPA

	FM Surplus	SM Surplus	Revenue	Efficiency
$p = 0$	5.149***	2.671*	−6.379***	0.004
	(3.37)	(1.75)	(−3.10)	(0.57)
$p = 1/4$	2.983*	−0.759	−1.850	0.011
	(1.82)	(−0.35)	(−1.07)	(1.54)
$p = 1/2$	5.352***	−0.523	−3.289	0.021***
	(3.33)	(−0.19)	(−1.61)	(2.70)
$p = 3/4$	6.330***	−5.972**	0.478	0.021**
	(4.05)	(−2.18)	(0.23)	(2.43)
N	2304	2304	2304	2304

Notes: Marginal effects of mechanism (SPA − FPA) based on linear mixed-effects regressions of outcome on mechanism interacted with treatment and period, with random intercept effects on participant nested in effect on matching group. t statistics in parentheses based on Huber White sandwich estimation of standard errors $*p < .1$; $**p < .05$; $***p < .01$.

comes into play, as leaks in FPA favor the second mover to the disadvantage of the first mover and the seller. In comparison, leaks have little effect in SPA due to the selected equilibrium. As a result, leaks eliminate the revenue dominance of first-price over second price auctions at least for leak probabilities $p = 1/4$ and $p = 3/4$. For $p = 1/2$ we still observe considerably higher prices in FPA, and once we exclude the first or the first two repetitions of every treatment from the analysis, this effect becomes significant ($\beta = -4.526, p = .028$ and $\beta = -5.185, p = .013$, respectively). Finally, overbidding and the systematic favoring of potentially weak second-movers by leaks in first-price auctions lead to higher efficiency in SPA for high leak probabilities.[22]

RESULT 7. *Without leaks, first-price auctions favor the seller at the expense of the bidders. Leaks shift surplus from the seller to the second mover, eliminating the revenue dominance of first-price auctions in most treatments, and resulting in higher second-mover profits in first-price auctions.*

V. CONCLUSION

The most prominent auction formats are first- and second-price sealed-bid auctions, along with their strategically equivalent Dutch and (for independent private values) English auctions. Previous experimental evidence suggests that, in case of independent private values, the first-price rule generates higher seller revenue, while the second-price rule is more efficient[23] but prone to ring formation.[24] While research has looked into effects of private value revelation, informing late bidders about earlier bids has, to the best of our knowledge, so far been neglected.

Firms can be large organizations with various shareholders and stakeholders. Especially for complex custom goods and services, firms go through protracted price finding procedures involving various levels of management. At every stage one risks that information about the bidding strategy may be leaked to competitors. For example, the winner in an ascending bid auction for building rights is often required to make a down payment. If this has to be pre-approved or a credit line must be negotiated, there are many such opportunities. In addition to industrial espionage and corruption, early bids can also be revealed in error.

Our theoretical analysis questions stylized empirical facts from private value auctions without revelation of early bids. Moreover, comparative statics across price rules are ambiguous due to multiple equilibria in second-price auctions. The experimental outcomes of the first-price auctions are as (game-) theoretically predicted: Unconditional bids are not affected by leak probability, but actual leaks reduce seller revenue, overall efficiency, and first mover payoff while increasing that of second movers. Interestingly, these qualitative effects hold in spite of significant deviations from equilibrium bidding by first movers and uninformed second movers.

For both price rules, bids by informed second movers are overwhelmingly rational. In the second price auction, where informed second bids are crucial for equilibrium selection, we identify two crucial behavioral regularities. First, the majority of bids approximate one of the three focal types; truthful, spiteful, or cooperative. Second, we see individual consistency in bidding patterns. Which bidding type is more prevalent in application should depend on context. Imagine, for example, a firm bidding in an English auction who suspects that its rival (who is committed to participating in the auction) may have discovered its reserve price. How far should it expect

22. For leak probability $p = 1/4$ this effect is significant once we exclude either the first or the first two repetitions from the analysis, with $\beta = 0.014, p = .092$ and $\beta = 0.020, p = .004$, respectively.

23. Heterogeneous risk aversion is able to rationalize both phenomena.

24. Gandenberger (1961) shows that historically they were avoided in public procurement.

the rival to push the price? It is reasonable to assume that if the firms are competitors beyond the current auction, the rival is more likely to be spiteful than if the firms are otherwise in complementary relations. Nonetheless, we show that even in minimal laboratory settings that are free of such broad incentives and considerations, individuals have basic preferences that guide their biddings. Furthermore, all three focal types are fairly prevalent in the population. This insight is generalizable across many applications, even if the specific distribution of bidder types is not.

Our behavioral conclusions are in line with those of (Andreoni, Che, and Kim (2007), who similarly manipulate information of bidders about their opponents. In their experiment with four bidders *valuations* rather than *bids* of others may be revealed. Thus, their setting does not invoke strategically adjusted unconditional bids in second-price auctions, which is one focus of our theoretical and experimental analysis. Notwithstanding, we share some of Andreoni, Che, and Kim's (2007) conclusions, namely that weakly dominated bids are rare and less frequent with more experience; that behavior is qualitatively consistent with the comparative statics in first-price auctions; and that a substantial proportion of second movers with no chance of gaining from winning the auction overbid their own value while still underbidding the earlier bid, suggesting spiteful bidding. Unlike Andreoni, Che, and Kim (2007), we observe substantial cooperative bidding, which can be explained by a fundamental difference between their and our setup: rational losers in our experiment *know* when the first bid is above their valuation, whereas in Andreoni, Che, and Kim (2007) this holds only if others bid truthfully. In the latter case, possible bid shading by others may deter cooperative bidding.[25]

We can make some tentative predictions that go beyond the uniform distributions used in the experiment for reasons of better participant comprehension. Arozamena and Weinschelbaum (2009) showed theoretically that leaks in first-price auctions should not affect bidding behavior of uninformed bidders under power function distributions. Our experiments confirm this invariance for uniform distributions, which is a special case of more general power distributions. In second price auctions, moving to different distributions may arguably affect equilibrium selection, but not our main result, namely that equilibrium selection is systematic and individually consistent.

One straightforward extension of our model could introduce marginal entry costs. In this case, if the leak occurs before the entry commitment, rational losers are expected to abstain from bidding, and consequently only the cooperative second price auction equilibrium remains. Other interesting questions arise from endogenizing the leak probability in the sense of espionage or strategic leaks. In our setting, incentives for engaging in espionage are stronger in first- than second price auctions. Further research, both theoretical and experimental, may explore this for endogenous leaks.

APPENDIX: THEORETICAL ANALYSIS

PROOF OF PROPOSITION 1

Proof. To solve the first-price auction, first look at bidder 2's optimal bid $b_2(b_1, v_2)$ after seeing b_1, bidder 1's bid.[26] If $b_1 \leq v_2$, bidding $b_2(b_1, v_2) = b_1$ would let bidder 2 win at the lowest possible price. For $b_1 > v_2$, bidder 2 underbids b_1 (by how much does not affect the outcome). Thus, in equilibrium

$$b_2(b_1, v_2) \begin{cases} = b_1 & \text{if } b_1 \leq v_2, \\ < b_1 & \text{otherwise.} \end{cases}$$

When chance prevents an information leak, assume $b_1(v_1)$ and $b_2(\emptyset, v_2)$ to be monotonically increasing in the own value v_1 and v_2, with inverse functions $v_1(b_1)$ and $v_2(b_2)$, respectively. Without loss of generality, assume that $u_1(0) = u_2(0) = 0$. Expected optimality requires for bidder 2

$$\pi_2(v_2) = \max_{b_2} F(v_1(b_2))u_2(v_2 - b_2). \tag{A.2}$$

Similarly, bidder 1 tries to maximize

$$\pi_1(v_1) = \max_{b_1} [pF(b_1) + (1-p)F(v_2(b_1))]u_1(v_1 - b_1). \tag{A.3}$$

The first-order conditions from (A.2) and (A.3) are

$$F'(v_1(b_2))v_1'(b_2)u_2(v_2(b_2) - b_2) = u_2'(v_2(b_2) - b_2)F(v_1(b_2)),$$

$$[(1-p)F'(v_2(b_1))v_2'(b_1) + pF'(b_1)]u_1(v_1(b_1) - b_1) = u_1'(v_1(b_1) - b_1)[(1-p)F(v_2(b_1)) + pF(b_1)].$$

For F uniform and CRRA utility, the first-order conditions reduce to

$$v_1'(b_2)(v_2(b_2) - b_2) = (1-r)v_1(b_2),$$

$$[(1-p)v_2'(b_1) + p](v_1(b_1) - b_1) = (1-r)[(1-p)v_2(b_1) + pb_1],$$

with the unique solution $v_1(b_1) = (2-r)b_1$ and $v_2(b_2) = (2-r)b_2$, what proves Proposition 1 ■

25. Roth and Ockenfels (2002), for example, suggest that expecting bid shading from others in second-price auctions provides a (partial) explanation for sniping in online auctions.

26. Whenever we speak optimal of "optimal" or "rational" behavior, we assume opportunistic preferences, either in combination with risk neutrality or risk aversion.

DERIVATION OF COROLLARY 1

For bidder 1 the expected surplus depends on v_1 via

$$\pi_1(v_1) = \left[p\frac{v_1}{2} + (1-p)v_1\right]\left(\frac{v_1}{2}\right) = \left(1 - \frac{p}{2}\right)\frac{v_1^2}{2}.$$

Thus bidder 1's expected profit is

$$E[\pi(v_1)] = \left(1 - \frac{p}{2}\right)\frac{1}{2}E[v_1^2] = \left(1 - \frac{p}{2}\right)\frac{1}{2}\int_0^1 v_1^2 dv_1$$
$$= \frac{1}{6} - \frac{p}{12}.$$

When uninformed, bidder 2's expected surplus is $\pi_2(v_2) = \frac{v_2^2}{2}$. Ex ante this yields $E[\pi_2(v_2)] = E\left[\frac{v_2^2}{2}\right] = \frac{1}{6}$. When bidder 2 is informed about b_1 and $v_2 \geq \frac{1}{2}$, bidder 2 expects to earn $v_2 - \frac{1}{4}$, whereas for $v_2 \leq \frac{1}{2}$, informed bidder 2 can expect v_2^2. Ex ante informed bidder 2 expects $\int_0^{\frac{1}{2}} v_2^2 dv_2 + \int_{\frac{1}{2}}^1 \left(v_2 - \frac{1}{4}\right) dv_2 = \frac{1}{24} + \frac{1}{2} - \frac{1}{8} - \left(\frac{1}{4} - \frac{1}{8}\right) = \frac{7}{24}$. Thus, bidder 2's total expected profit is $p\frac{7}{24} + (1-p)\frac{1}{6} = \frac{1}{6} + \frac{p}{8}$.

When F is uniform, with probability $1-p$ revenue equals $\max\{v_1, v_2\}/2$ as usual. With probability p, however, the revenue equals $v_1/2$, and therefore total expected revenue is

$$(1-p)E\left[\frac{\max\{v_1, v_2\}}{2}\right] + pE\left[\frac{v_1}{2}\right]$$
$$= (1-p)\cdot\frac{1}{3} + p\frac{1}{4} = \frac{1}{3} - \frac{p}{12}.$$

Since for efficiency, the sum of all expected surpluses of the seller and both bidders should be $\frac{2}{3}$, the efficiency loss is $\frac{2}{3} - \left(\frac{1}{3} - \frac{p}{12}\right) - \left(\frac{1}{6} - \frac{p}{12}\right) - \left(\frac{1}{6} + \frac{p}{8}\right) = \frac{p}{6} - \frac{p}{8} = \frac{p}{24}$. We summarize the above in the following Corollary.

PROOF OF PROPOSITION 4

Proof. For SP-Truthful, since $g(b_1, v_2) = v_2$ is independent of b_1, the RHS of (3) equals 0. The LHS can only be 0 if $v_1 = b_1$. For SP-Spiteful, when $g(b_1, v_2) = b_1$, (3) becomes

$$\text{(A.4)} \qquad \frac{u(v_1 - b_1) - u(0)}{u'(v_1 - b_1)} = p \cdot \frac{F(b_1)}{F'(b_1)}.$$

The derivative of the left-hand side with respect to v_1 equals $1 - \frac{(u(v_1-b_1)-u(0))u''(v_1-b_1)}{u'(v_1-b_1)^2}$. When u is strictly concave, this is strictly greater than 1 for all $v_1 > b_1$. For risk neutrality, it is equal to 1. Hence, when finding the inverse bid function for the same bid, when utility is concave, $v_1 - b_1$ must be smaller. This implies that bids are higher with concavity than risk-neutrality.

For SP-Cooperative ($g(b_1, v_2) = 0$), (3) becomes

$$\text{(A.5)} \qquad pu(v_1) + (1-p)u(v_1 - b_1) = u(0).$$

This easily reduces to our result for risk neutrality.

Note in general that $b_1 > v_1$ due to monotonicity of utility and (A.5). Concavity of utility implies a decreasing slope so that when $v < b$:

$$\text{(A.6)} \qquad \frac{u(v) - u(0)}{v} < \frac{u(0) - u(v-b)}{0 - (v-b)}.$$

After rewriting this becomes

$$\text{(A.7)} \qquad (u(v) - u(0))\frac{b-v}{v} < u(0) - u(v-b).$$

With risk neutrality (A.5) becomes:

$$\text{(A.8)} \qquad pv_1 + (1-p)(v_1 - b_1^n) = 0.$$

Combining yields

$$\text{(A.9)} \qquad (u(v_1) - u(0))\frac{p}{1-p} < u(0) - u(v - b_1^n).$$

Since (A.5) implies $(u(v_1) - u(0))\frac{p}{1-p} = u(0) - u(v_1 - b_1)$, we must have $b_1 < b_1^n$. ∎

DERIVATION OF REMARK 1

Substituting the CRRA utility into (A.4) yields the CRRA result with respect to SP-Spiteful.

With SP-Cooperative, for CARA preferences (A.5) becomes $e^{r\cdot v_1} = p + (1-p)e^{r\cdot b_1}$. This implies $b_1 > v_1$ since $e^{r\cdot x} > 1$ for $r, x > 0$ and is increasing in x. Solving for the inverse bid function yields

$$v_1 = \frac{1}{r}Log(p + (1-p)e^{r\cdot b_1}).$$

The derivative w.r.t. to r is proportional to

$$\frac{be^{br}(1-p)r}{e^{br}(1-p)+p} - Log(p + e^{br}(1-p)).$$

This is 0 when $r = 0$ and the derivative w.r.t. r is proportional to

$$b^2 e^{br}(1-p)pr$$

which is strictly positive when p is interior and $r > 0$. Hence v_1 is increasing in r and bidding is decreasing in r.

OUTCOMES IN SPA

We derive bidder surplus, seller revenue and total efficiency for the three focal equilibria in SPA.

Outcomes in SP-Truthtelling

In the SP-Truthtelling equilibrium neither bids of bidder 1 nor bidder 2 are affected by the leak probability and therefore all ex-ante expected outcomes are as in the standard simultaneous case.

Outcomes in SP-Spiteful Bidding

For F uniform and spiteful bidding, we have $b_1(v_1) = \frac{v_1}{1+p}$. In the SP-Spiteful equilibrium, bidder 1's expected surplus is

$$p\int_0^1 \frac{v_1}{1+p}\left(v_1 - \frac{v_1}{1+p}\right)dv_1$$
$$+ (1-p)\int_0^1 \frac{v_1}{1+p}\left(v_1 - \frac{v_1}{2(1+p)}\right)dv_1$$
$$= \frac{1}{6(1+p)},$$

and bidder 2's expected surplus is

$$p \cdot \int_0^1 \left(1 - \frac{v_1}{1+p}\right)\left(1 - \frac{v_1}{1+p}\right)\frac{1}{2}dv_1$$

$$+ (1-p)(1+p)\int_0^{\frac{1}{1+p}} (1-b_1)^2 \frac{1}{2} db_1$$

$$= \frac{1 + 3p(1+p)}{6(1+p)^2}.$$

The seller's revenue is

$$p\frac{1}{2(1+p)} + (1-p)$$

$$\times \int_0^{v_1} \left[\frac{v_1}{1+p} \cdot \frac{v_1}{2(1+p)} + \left(1 - \frac{v_1}{1+p}\right)\frac{v_1}{1+p}\right] dv_1$$

$$= \frac{1+2p}{3(1+p)^2},$$

and thus, the efficiency loss is

$$\frac{p^2}{6(1+p)^2}.$$

Outcomes in SP-Cooperation

In the SP-Cooperation equilibrium, bidder 1's expected surplus is

$$p \cdot \int_0^{1-p} \frac{v_1}{1-p} \cdot v_1 dv_1 + p^2 \cdot \frac{2-p}{2}$$

$$+ (1-p)\left[p\left(\left(1 - \frac{p}{2}\right) - \frac{1}{2}\right) + (1-p)\right.$$

$$\left.\times \int_0^1 \int_0^{b_1} (b_1(1-p) - b_2) db_2 db_1\right]$$

$$= \frac{1+p+p^2}{6},$$

and bidder 2's expected surplus equals

$$p \cdot \int_0^{1-p} \left(1 - \frac{v_1}{1-p}\right)\left(1 - \frac{v_1}{1-p}\right)\frac{1}{2}dv_1$$

$$+ (1-p)(1-p) \cdot \frac{1}{6} = \frac{1-p}{6}.$$

The expected revenue is

$$p \cdot \int_0^{1-p} \left(1 - \frac{v_1}{1-p}\right)\frac{v_1}{1-p}dv_1$$

$$+ (1-p)\left(\frac{p}{2} + \frac{1-p}{3}\right) = \frac{1-p^2}{3}.$$

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Appendix S1. Auxiliary data analysis

Appendix S2 Instructions