The Candle Auction in the Field and the Lab*

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Abstract

This paper investigates ascending combinatorial auctions with random ending times — known as candle auctions — through theoretical analysis, field data, and laboratory experiments. We derive conditions under which candle auctions are approximately efficient. Field data from blockchain auctions confirm that bids escalate early, and the top bidder at the end typically wins at the random closing time. In the lab, candle auctions perform comparably to auctions with hard or soft closing rules regarding efficiency and revenue. Still, they are more robust to collusion, highlighting their potential as a reliable format in strategic environments where collusion is difficult to prevent. *JEL Classifications*: C91, C93, D44.

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1 Introduction

In dynamic auctions, where bids are placed continuously over time, *closing rules* determine when and how the auction ends. Two common rules are the *hard-close* rule, in which the auction ends at a predetermined time, and the *soft-close* rule, which extends the auction as long as bidding activity continues. Both are widely used in procurement, online, and spectrum auctions. The soft-close rule is often favored over the hard-close rule because it discourages strategically timed bidding behaviors—such as sniping, jump bidding, or delayed bidding—that can reduce efficiency and revenue (e.g. Roth and Ockenfels, 2002). However, its main drawback is that it can lead to excessively long auctions. This paper studies an alternative: the *random-close rule*, which avoids lengthy durations, prevents sniping, and appears to offer greater resistance to bidder collusion.

Under the *random-close rule*, the auction may end at any moment with positive probability. The highest bidder at the time the auction ends is declared the winner and pays their bid. Dynamic auctions with this rule are known as *candle auctions*, and we use the two terms interchangeably throughout this paper. Originating in medieval Europe, candle auctions take their name from a practice in which the auctioneer would light a candle in full view of the bidders and accept bids until the flame went out. The highest bidder at that moment won the auction (e.g. Hobson, 1971). The earliest recorded instances date back to 14th-century France, where candle auctions were used to sell chattels and leases. In England, they remained in use for the sale of furs through the 18th century (cf. Füllbrunn and Sadrieh, 2012, for more details and references)

Today, random-close rules are still used in modern settings. They are employed in procurement auctions run by the Brazilian government (Celiktemur and Szerman, 2012; Fernandes De Oliveira et al., 2019) and on certain stock exchanges (Cordi et al., 2017). More recently, candle auctions have been adopted in online auctions conducted on the blockchain networks Polkadot and Kusama (see details below).

In this paper, we attempt to study the candle auction from theoretical, empirical, and experimental perspectives. We begin our study in Section 3 by providing a theoretical analysis of an ascending, open-outcry candle auction with a single good. The auctioneer commits to a random closing time that he announces retroactively, i.e., once the auction has run for a predefined amount of time. Bids can be entered until the end; the highest bidder at the closing time wins and pays their bid. We show that the candle auction has an approximate ex-post equilibrium in strategies under which bidding escalates almost immediately and stops at the second-highest bid (plus one increment). Intuitively, it is never optimal for a bidder to leave the highest bid to an opponent because the end of the auction may be at any instance. This finding implies that the candle auction is efficient and optimal.

Both our field and experimental data are drawn from combinatorial candle auctions.[1] Combinatorial auctions are the standard mechanism for selling multiple complementary goods in many practical applications, such as radio spectrum Porter and Smith (2006); Cramton (2013), electricity (Meeus et al., 2009), and bus routes (Cramton et al., 2005). To help bidders better determine their optimal bidding strategy, many combinatorial auctions take time to conclude, with the ascending format being particularly popular (e.g., Brunner et al., 2010). Our analysis of the single-good case helps us build intuition and discipline our hypotheses about bidding behavior for the combinatorial candle auction. In particular, our results suggest early bid escalation even in the face of a coordination problem inherent to the combinatorial setup (Chernomaz and Levin, 2012). In the case of strong value complementarities across packages, our single-good result extends and again shows that incremental bidding on all relevant packages is an approximate ex-post equilibrium.

Our field data are drawn from a series of auctions conducted between 2022 and 2024 on two blockchain platforms called Polkadot and Kusama. Polkadot, like its better-known peer Ethereum, is a blockchain platform, though with a distinct focus on enabling interoperable

[1]In fact, we designed the experiment as such after learning of the auction rules in the field. As it turned out, however, bidders in the field setting had low demand for sub-packages such that the combinatorial feature in the field data was less relevant than we expected.

and application-specific blockchains for secure data storage, bookkeeping, and computational resources. Kusama serves as a test network for many firms to develop products that they later launch on Polkadot. The networks can be compared with traditional cloud computing and storage services but instead of relying on centralized infrastructure, the services are provided by a decentralized network of servers and secured with a blockchain (we provide more details in Section 4). These features enable a variety of use cases such as decentralized exchanges, cloud storage, rendering services, and supply chain management (see Mohanta et al., 2018, for an overview).

Polkadot and Kusama sell fixed data bandwidth to use their services in recurrent combinatorial candle auctions, where the bidders can bid on packages of so-called *lease periods* of 1.5-6 months over the following two years.[2] We analyze data from 70 auctions, with total winning bids amounting to approximately $1.37 million USD. Each auction ran over a fixed period of roughly seven days, after which the winning time was determined. As expected from theory, the bidders bid aggressively early in the auctions. We find that in most auctions, the revenue is not much less than the revenue that would accrue if the closing time were at the very end of the auction. Moreover, the bidders with one or more bids in the winning allocation at the end of the auction are also among the winners at the random closing time. We take this as indicative that the candle auction is close to optimal and highly efficient.

A caveat with this efficiency measure is that we do not observe the actual valuations of the bidders. Therefore, in Section 5, we supplement our empirical analysis with experiments where we can control for valuations. We ran multiple series of auctions between three bidders competing for two items that can be obtained either together or individually. One bidder (we call her the inflexible bidder) has a positive valuation only for obtaining both packages. The other two bidders are flexible and have (additive) values for each of the individual packages.

[2] Auctions are popular selling and allocation mechanisms in blockchain markets. For an example of a combinatorial auction used for procuring the execution of trades across various platforms, see Canidio and Henneke (2025).

We consider this setup because it is the simplest combinatorial setup that allows us to study questions of efficiency, optimality, and coordination among the bidders.

An additional advantage of running experiments is that they allow comparisons to other auction formats. Specifically, we compare the random-close rule to a hard-close rule and an soft-close rule with an automatic extension if the last bid was entered less than 10 seconds before the end. The experimental candle auction shows high efficiency, implying that the highest valuing bidders must have been in the lead throughout the auction. We do not find a significant difference across auction formats regarding efficiency or revenues. Also, coordination among the flexible bidders is not affected by the specific closing rule.

A special focus of our analysis is on collusion. A key feature of the online auction setting we study (and many other online auctions) is that (hidden) communication between participants is cheap to do for the participants and almost impossible to prevent for the auctioneer. Thus, we included a chat system that allows participants to discuss their strategies freely before each auction. Analyzing the chat protocols of the bidders before and between auction rounds, we can show that the soft-close rule is most prone to collusion, while the candle auction is not. We provide evidence that the collusion-proofness of the candle auction indeed drives our findings.

With these findings, we add to the literature examining the relationship between communication and collusion in finitely repeated auction experiments. For example, it has been shown that communication facilitates collusion in one-shot single-good auctions (Agranov and Yariv, 2018). In combinatorial auctions, the clock format is more prone to explicit collusion than static variants (Burtraw et al., 2009). The collusive strategies discussed by the subjects in our experiment take the form of turn-taking, where bidders alternate in letting each other win an auction with very low bids. Turn-taking was observed, e.g., by Cason et al. (2013), but this was in an indefinitely repeated game. In our setting with 10 fixed auctions of which only one was randomly chosen for payment, turn-taking does not survive backward induction. Yet, it seems that some bidders were quite successful in convincing their competitors of the scheme, which resulted in very high payoffs for them (more than 100 Euro).

An aspect of the soft-close rule that, to our knowledge, has not been previously noted in the literature is that it creates a perfect environment for collusive agreements within auctions.[3] If bidders deviate from turn-taking, they cannot do so at the last moment because, under the soft-close rule, there is no last moment to place a bid. On the other hand, in hard-close auctions, sniping may reduce the stability of collusion. Why candle auctions are so robust against collusion, however, remains an open question since they should suffer from the same problem as the soft-close rule.

The remainder of the paper is organized as follows. Section 2 discusses the related literature. Section 3 provides the theoretical analysis, Section 4 analyzes the field data, and Section 5 covers our experiment. The last section concludes. Proofs, screenshots from the experiment, the instructions, their translations, and the quiz are documented in Online Appendices A–F.

2 Literature

Our paper primarily contributes to the experimental literature on closing rules in ascending auctions and to that on dynamic combinatorial auctions.

The seminal work on closing rules in auctions is Roth and Ockenfels (2002), establishing that late bidding (or "sniping") is far more prevalent in single-good online auctions with a hard-close rule than in those with a soft-close rule. Ariely et al. (2005) provides experimental support for this finding, showing that as bidders gain experience, they increasingly adopt late-bidding strategies under hard-close rules but avoid them under soft-close rules. Ockenfels

[3] Recently, there have been a few experimental studies on the role of auction rules for collusion (e.g. Fugger et al., 2016; Hinloopen et al., 2020; Noussair and Seres, 2020, in addition to the papers mentioned above). Yet, to our knowledge, no study explicitly analyzes the role of the soft-close rule. We review the experimental literature on collusion in (repeated) auctions in Section 2.

and Roth (2006) demonstrate theoretically that sniping is a rational response to incremental bidding in hard closing auctions. Furthermore, Backus et al. (2015) revealed that bidders who were sniped on eBay were significantly less likely to participate in future auctions. None of these studies examined the implications of a random-close rule.[4]

The seminal papers on combinatorial auctions in the laboratory include Goeree and Holt (2010) and Brunner et al. (2010), which compare the traditional ascending multi-item auction — where bids are placed only on individual items — to combinatorial auctions with various packaging restrictions. One noteworthy mechanism is hierarchical package bidding (HPB), later adopted by the FCC. These studies find that in settings with value complementarities, combinatorial auctions outperform traditional formats in terms of efficiency and revenue. Further, Scheffel et al. (2012) compare the HPB mechanism introduced by Goeree and Holt (2010) to a clock auction format, while Bichler et al. (2013) analyze the combinatorial clock auction versus the ascending multi-unit auction, yielding mixed results. Bichler et al. (2017) examine coordination in ascending package auctions with many items, proposing a scheme to provide bidders with information during the auction. In our study, we deliberately use a simple item structure comprising three packages to isolate the effects of the (random) closing rule.[5]

To our knowledge, the only other experimental study of the random-close rule is Füllbrunn and Sadrieh (2012), who investigate single-good auctions with a second-price payment rule. They find that truthful bidding immediately is an equilibrium strategy in this setting, a result largely confirmed by their experiments. The strategic dynamics in our setting, which employs a first-price payment rule, are more complex. Empirical studies on the random-close rule include Cordi et al. (2017), who find that randomly closing double auctions in certain

[4]The role of ending times is also discussed in financial markets more generally; cf. Kopányi-Peuker and Weber (2024) for an overview of the experimental evidence.

[5]Our findings suggest that coordination issues persist even in settings with a small number of packages, regardless of the closing rule.

stock markets can improve price discovery. Celiktemur and Szerman (2012) and Fernandes De Oliveira et al. (2019) study the random-close rule in Brazilian procurement auctions, reporting mixed evidence on bidding behavior, showing that many bids are submitted fairly late in the auction. A first theoretical treatment of the single-good candle auction is Malaga et al. (2010), who analyze the first-price rule under restricted strategies and ending-time distributions.[6] Celiktemur and Szerman (2012) find an equilibrium similar to that in Füllbrunn and Sadrieh (2012) for the second-price rule. Lately, Häfner and Stewart (2024) analyze single-good open-outcry auctions in the presence of information leakages about other bidders' actions and show that efficiency and optimality can be restored with a suitably chosen ending-time distribution.

Finally, our findings contribute to the literature on collusion in auctions. Collusion has long been recognized as a significant concern, particularly in repeated auction settings (e.g., Hendricks and Porter, 1989; Pesendorfer, 2000). Theoretical studies on collusion in repeated auctions, often through bid-rotation schemes, include Aoyagi (2003), Skrzypacz and Hopenhayn (2004), and Che and Kim (2009).[7] Studies on collusion in individual (non-repeated) auction settings include Marshall and Marx (2009), who analyze ascending and second-price single-good auctions, and Fugger et al. (2016), who examine reverse-price auctions. The work most closely related to our setup is Brusco and Lopomo (2002), who demonstrate the existence of collusive equilibria in ascending multi-unit auctions.[8] However, none of these studies consider the role of the closing rule in facilitating or deterring collusion, which is a central focus of our findings.

[6] Specifically, Malaga et al. (2010) restrict the bidders to incremental bidding strategies and waiting between bids, and they only consider ending-time distributions with a weakly concave CDF. Our theoretical results show that incremental bidding is indeed an (approximate) best response to incremental bidding when the waiting times vanish, irrespective of the ending-time distribution. We also extend our analysis to combinatorial auctions.

[7] Lengwiler and Wolfstetter (2010) examine auctions involving corrupt auctioneers.

[8] See Füllbrunn (2011) for a discussion of the closing rule in such a setting.

The relationship between auction rules and the presence of collusion has been the subject of several experimental studies. Fugger et al. (2016) find evidence of collusion in reverse-price auctions with stochastic attribute weighting by the buyer. Like in our setup, Agranov and Yariv (2018) allowed the subjects to chat before the auctions. They find that collusion leads to lower revenues, yet the auction format (one-shot sealed-bid first-price vs second-price) had no effect. Burtraw et al. (2009) analyze multi-unit auctions and allowed for oral communication. They find higher collusion in the clock auction format than in the one-shot uniform and discriminatory format, conjecturing that the dynamic structure facilitated collusion. Some studies also analyze the role of implicit collusion (i.e., without communication) in repeated auctions (Sherstyuk, 1999; Hu et al., 2011; Hinloopen et al., 2020; Noussair and Seres, 2020). Both Sherstyuk (1999) and Hinloopen et al. (2020) compare first-price auctions to English auctions, finding more collusive outcomes in the latter.

3 The Candle Auction in Theory

In this section, we delineate bidders' incentives and discuss equilibrium in the candle auction. In the first subsection, we focus on the single-good case for simplicity and establish the existence of an ex-post equilibrium in incremental strategies. Then, we give a sufficient condition for an incremental bidding equilibrium to also exist in the combinatorial variant. Finally, we present our hypotheses for both the field and the lab.

3.1 The Single-Good Case

Environment We consider the following environment. There are $n \geq 2$ bidders $i = 1, ..., n$ having IPV v_i for a single good on sale. The values are drawn from a symmetric discrete distribution on $V := \{0, \Delta, 2\Delta, ..., 1\}$ having CDF F, which is common knowledge. We assume $\Delta > 0$ to be arbitrarily small and $1/\Delta$ to be an integer. We normalize the auction length to unity and index time by $t \in [0, 1]$. A candle auction concludes at some random ending time T, where we take T to be uniformly distributed on $[0, 1]$.

Bids need to be on a grid $B := \{0, \Delta, 2\Delta, ..., \bar{b}\}$, where we take the highest possible bid $\bar{b} \in \mathbb{Q}_+$ to be strictly higher than 1 so that it never binds in equilibrium.[9] Bidders can submit their bids at discrete points of time during $[0, 1]$, namely at any point in the grid

$$T_m := \left\{ \frac{1}{m}, \frac{2}{m}, ..., 1 \right\}. \tag{1}$$

Throughout we assume $\frac{1}{m\Delta} < 1$. Specifically, we are interested in equilibrium behavior when $m \to \infty$; that is, when T_m becomes dense in $[0, 1]$. We follow the literature here in modeling the continuous-time game as the limit of discrete-time games (see, e.g. Simon and Stinchcombe, 1989).

The history of play at time t, h_t, comprises all the bids up to (but excluding) time t and the bidders' identities. A strategy of bidder i is $\beta_i = (\beta_{it})_{t \in T_m}$, where $\beta_{it}(h_t, v_i) \in B \cup \{\emptyset\}$ describes the bid that bidder i with value v_i submits at time $t \in T_m$ after a history h_t, with $\emptyset$ meaning that no (new) bid is submitted. The ending time T is announced retroactively, i.e., after the auction has ended in $t = 1$. The bidder with the highest bid at the ending time T wins the object and pays her bid. Ties are broken in favor of the earliest winning bid; if there are multiple earliest winning bids, then ties are broken randomly. In case no bids have been entered at T, no one obtains the good.

Equilibrium In English auctions that end as soon as no further bids are entered, incremental bidding, where a bidder submits a bid equal to the previous bid plus the minimum increment Δ as long as the resulting bid is less than her valuation, is a weakly dominant strategy when simultaneous bids are considered in a deterministic priority order (Daniel and Hirshleifer, 2018). Maybe somewhat surprisingly, dominance of incremental bidding fails to

[9]The set of values and the set of feasible bids need not be spaced by the same increment for the gist of the main result to go through, but it facilitates both the exposition and the proof.

hold true in candle auctions, irrespective of the tie-breaking rule.[10]

To see this, consider a candle auction with two bidders. Bidder 1 has a valuation $v_1 > 2\Delta$. Bidder 2 has the admittedly weird but possible strategy of bidding Δ right at the start. If at any time $t < 1/2$, bidder 1 makes any positive bid, bidder 2 will respond in the next moment by the maximal bid $\bar{b}$. Otherwise, bidder 2 does not bid again. Obviously, bidder 1's payoff from incremental bidding would approach zero as $m \to \infty$. However, the strategy "bid nothing up to $t = 1/2$, bid 2Δ afterwards" yields payoff $[v_1 - 2\Delta]\frac{1}{2} > 0$. Hence, incremental bidding is not even approximately weakly dominant, which complicates the proof of Proposition 1 below substantially.[11]

Nevertheless, we can show that incremental bidding is an approximate ex-post equilibrium in the candle auction. Specifically, we require the strategies to be approximate ex-post best replies in every stage, i.e., after any round t and history of play h_t, which we refer to as stage-wise ex-post ϵ-equilibrium in the following.[12] To formally define equilibrium, let $U_{it}(\beta, v; h_t)$ be bidder i's expected continuation utility at time t after a history h_t, unconditional on the ending time having occurred before time t, when the bid strategy profile is $\beta = (\beta_1, ..., \beta_n)$ and the profile of valuations is $v = (v_1, ..., v_n)$.[13]

Definition 1 (Stage-Wise Ex-Post ϵ-Equilibrium). *A stage-wise ex-post ϵ-equilibrium is a*

[10] Dominance of incremental bidding also fails to hold in the ascending auction with a hard closing ending rule and proxy-bidding, when last-instance bids might not arrive in time (Ockenfels and Roth, 2006).

[11] In the English auction, however, there is no benefit of waiting. If bidder 1 does not bid, the auctioneer will stop the auction, and bidder 1's payoff is zero. Hence, whenever bidder 1 is behind, she could just as well increase her bid unless her value is reached.

[12] An early reference to ex-post equilibrium is Crémer and McLean (1985). Ex-post equilibrium (in static games) is a popular concept in robust mechanism design because it is invariant in the player's beliefs (Bergemann and Morris, 2005; Jehiel et al., 2006). As in the static setting, ex-post in our setting refers to bidders knowing the profile of valuations.

[13] We define equilibrium by taking the unconditional utility because the ending time is announced retroactively; i.e., the bidders do not know during the auction if the ending time has already occurred.

bid strategy profile β^* *such that, for all value profiles* v *and all bidders* $i \in \{1, ..., n\}$,

$$U_{it}(\beta^*, v; h_t) + \epsilon \geq U_{it}(\beta_i, \beta^*_{-i}, v; h_t), \ \forall \beta_i,$$

holds for all times $t \in [0, 1]$ *and all feasible histories* h_t.

The interpretation is as follows: No matter what happened before t in the auction, and even if a bidder learned the values of her opponents in t, she could not gain more than some small amount by deviating from her equilibrium strategy after t.

We construct an equilibrium in Markov strategies, which we call *incremental bidding* in the following. The payoff-relevant state at any point t is $s = (b^{max}, N)$, where $b^{max} \in B$ is the value of the highest bid up to (but excluding) t and $N \subseteq \{1, ..., n\}$ is the set of bidders having submitted the highest bid. The initial state involves $b^{max} = 0$ and $N = \{1, ..., n\}$.

Definition 2 (Incremental Bidding)**.** *A strategy* β_i *is called incremental bidding if, for all* $t \in T_m$ *and* h_t *corresponding to a state* s*, the bidder bids according to* $\mu_i(s, v_i) \in B$*, where*

$$\mu_i(s, v_i) = \begin{cases} \emptyset & \text{if either (i) } i \in N \text{ and } |N| = 1, \text{ or (ii) } b^{max} \geq v_i - \Delta \\ b^{max} + \Delta & \text{else.} \end{cases} \tag{2}$$

Under incremental bidding, a bidder increases the current highest bid by an increment Δ unless she is the only bidder holding the current highest bid (case i), or she would have to bid at or higher than her valuation (case ii). So, in equilibrium, the bidders will submit a bid of size Δ at the first bidding opportunity and then jointly increase the winning bid by Δ at every opportunity, with bidder i quitting the auction when the current highest bid is at $v_i - \Delta$. The last bidder in the auction stops bidding once she is the only bidder that has submitted the highest bid.

For the following, let $v_{(j)}$ be the realized j-highest valuation among the bidders. That is, $v_{(1)}$ is the valuation of the bidder with the highest valuation, $v_{(2)}$ is the value of the bidder with the second-highest valuation, and so on, and $v_{(n)}$ is the value of the bidder with the lowest valuation. The value $v_{(j)}$ can be weakly ordered; for example, if $v_{(1)} = v_{(2)} > v_{(3)}$, then we have two bidders with the highest valuation.

Proposition 1 (Incremental Bidding Equilibrium)**.** *Fix* $\Delta > 0$*.*

(i) For every $\epsilon > 0$*, there is a finite constant* $M > 0$ *such that for all* $m \geq M$*, the incremental bidding profile* $\beta^* = (\beta_1^*, ..., \beta_n^*)$*, where the strategies* β_i^* *are described by* (2)*, is a stage-wise ex-post* ϵ*-equilibrium.*

(ii) In the limit $m \to \infty$*, the resulting equilibrium revenue is within* Δ *of* $v_{(2)}$ *almost surely. The valuation of the winner corresponds to* $v_{(1)}$ *almost surely.*

In the continuous limit, $m \to \infty$, the bidders in the incremental bidding equilibrium described in Proposition 1 immediately bid up to $v_{(2)}$ (if there is a unique bidder with the highest value) or $v_{(2)} - \Delta$ (if there are multiple bidders with the highest value). The bidders with the highest value hold the highest bid for virtually the whole time $[0, 1]$. Consequently, the equilibrium revenue is approximately and the equilibrium allocation is exactly that of the second-price auction with probability one.[14]

A key intuition for why incremental bidding is an equilibrium is that the random ending time forces bidders to escalate their bids early in the auction. Other than in established closing rules like the hard-close rule or the soft-close rule, where early bids are inconsequential for winning, it is never in the interest of a bidder in the candle auction to let an early winning bid by an opponent stand. When the auction may terminate at any time, bidders want to keep having a winning bid at all times.

One worry with the candle auction is that the bidding escalation does not happen quickly enough, so a revenue loss will result when the ending time is early in the auction. Proposition 1 tells us that this risk is minimal for the single-good auction. Bids should rise quickly up

[14]Indeed, when the auction ends at $t = 0$, then revenue is equal to zero and the allocation is random even in the limit $m \to \infty$. However, this is a zero-probability event.

to the value of the second-highest bidder so that the resulting allocation is efficient with a very high probability and the payment is close to the theoretically achievable optimum.

3.2 The Combinatorial Candle Auction

Environment The combinatorial variant of the candle auction is as above, except that multiple goods in the set $Y = \{1, 2, \ldots, \ell\}$, $\ell \geq 2$, are on sale. Bidders can bid on any package from Y; i.e., on any non-empty element of the power set of Y, $X = 2^Y$. (In the field, we have $\ell = 4$ plus an additional side constraint; in the lab we work with $\ell = 2$.)

Bidder i's valuation is now a vector $v_i = (v_{ix})_{x \in X}$ describing her (private) values $v_{ix} \in V$ for obtaining the different packages $x \in X$. As before, the distribution of every bidder's valuation v_i is common knowledge. In each round, each bidder can submit bids on any package x. At the ending time T, the auctioneer selects a revenue-maximizing allocation. The bids are OR; that is, a bidder can have multiple (non-overlapping) winning bids.[15]

Analogous to the single-good auction, the tuple h_t contains the history of all bids (and the respective bidders) on all packages up to (but excluding) t. Then, the strategy of bidder i can be expressed by $\beta_i = (\beta_{ixt})_{x \in X, t \in T_m}$ where $\beta_{ixt}(h_t, v_i)$ returns the bid that bidder i places on package $x \in X$ at time t. In the combinatorial setting, the state is

$$s = (b_x^{max}, N_x)_{x \in X}.$$

Here, $b_x^{\max}$ denotes the current highest bid on package $x \in X$ and N_x collects the identities of the bidders that have submitted the current highest bid for package x. At the beginning of the auction, we set $b_x^{\max} = 0$ and $N_x = \{1, .., n\}$ for all $x \in X$.

In the case of a tie, preference is given to the earliest revenue-maximizing allocation. If there are multiple earliest such allocations, then the allocation is uniform. Let $\mathcal{W}_i(s) \subseteq Y$

[15] OR-bids are not the most expressive bidding language, but in the case of complementarities, as will be the case in our experiment, they are without loss (Nisan, 2000).

be the (possibly empty) package that would be allocated to bidder i with certainty (i.e., absent ties) if the auction ended in state s. Adapting the incremental bidding strategy to our setup, a bidder will continue to increase the current highest bid on any package x by one increment Δ unless she obtains a weakly higher joint utility from winning sub-packages of x instead, her value for package x is below the current highest bid, or she is the only holder of the winning bid on x and x is a (weak) sub-package of the package she wins for sure. To formalize this, let $\Pi(x)$ be the set of all partitions of the set x. Then,

Definition 3 (Incremental Bidding in the Combinatorial Auction)**.** *A strategy β_i is called incremental bidding if, for all $t \in T_m$ and h_t corresponding to a state s, the bidder bids on package x according to $\mu_{ix}(s, v_i) \in B$, where*

$$\mu_{ix}(s, v_i) = \begin{cases} \emptyset & \text{if (i) } v_{ix} \leq \max_{P \in \Pi(x) \setminus x} \sum_{y \in P} v_{iy}, \\ & \text{or (ii) } i \in N_x,\ |N_x| = 1,\ x \subseteq \mathcal{W}_i(s), \\ & \text{or (ii) } b_x^{max} \geq v_{ix} - \Delta \\ b_x^{max} + \Delta & \text{else,} \end{cases} \tag{3}$$

Condition (i) in the first case of (3) fails for all packages when values are strictly complementary; i.e., when for any two non-overlapping packages y and z it holds $v_{y \cup z} > v_y + v_z$. In the case of additive values (as in the example below) or, more generally, when all packages are substitutes, condition (i) implies that the bidder will bid only on the smallest possible packages (with positive value).[16]

The Coordination Problem In the combinatorial auction, an incremental-bidding equilibrium does not necessarily exist. This is due to a well-known coordination problem with a battle-of-the-sexes flavor when bidders have asymmetric demand (e.g., Chernomaz and Levin, 2012).

[16]Under the strong-complementarity-at-the-top assumption below, condition (i) fails for the largest package Y but not necessarily for other ones.

To see the problem, consider the following example with $Y = \{1,2\}$ involving a "large" bidder and two "small" bidders. Suppose $\Delta = 0.01$. Bidder $i = 1$ is the large bidder who values only the grand package, $v_{1\{1,2\}} = 1$ and $v_{1\{1\}} = v_{2\{2\}} = 0$. The two small bidders $i = 2, 3$ have additive valuations and prefer different small packages, $v_{i\{1,2\}} = v_{2\{1\}} = v_{3\{2\}} = 0.8$ and $v_{2\{2\}} = v_{3\{1\}} = 0$. Suppose the valuations are common knowledge. Clearly, the efficient allocation is to give package $\{1\}$ to bidder 2 and package $\{2\}$ to bidder 3.

Under incremental bidding from Definition 3, the large bidder bids on the package $\{1,2\}$ until $b^{max}_{\{1,2\}} = 0.99$. The small bidders bid on their preferred small package and increase their bid until $b^{\max}_{\{1\}} = b^{\max}_{\{2\}} = 0.5$. In the limit $m \to \infty$, the small bidders thus win almost surely and obtain payoffs 0.3 each. Yet, bidding incrementally is not a best response for everyone. Specifically, if both the large bidder $i = 1$ and the small bidder $i = 2$ were to follow incremental strategies, then the small bidder $i = 3$ would fare best to stop bidding when $b^{\max}_{\{1\}} = 0.21$, for then bidder $i = 2$ will incrementally bid up the price on package $\{2\}$ until $b^{\max}_{\{2\}} = 0.79$. In the limit $m \to \infty$, bidder 2's payoff is then 0.59. So, incremental bidding cannot even be an approximate equilibrium in the presence of a coordination problem.

A Sufficient Condition for Equilibrium Incremental bidding is an approximate equilibrium when the coordination problem is absent. The coordination problem is absent if the bidders' values are strongly complementary in the following sense. Let $\mathcal{A}_{-Y}$ be the set of feasible allocations other than the ones that give the full set of items Y to just one bidder,

$$\mathcal{A}_{-Y} := \Big\{(x_j)_{j\in\{1,\ldots,n\}} : x_j \in X \setminus Y, \forall j;\ x_j \cap x_k = \emptyset, \forall j \neq k;\ \bigcup_j x_j = Y\Big\}.$$

Definition 4 (Strong Complementarity at the Top)**.** *We say that bidders' values are strongly complementary at the top if, for all bidders i and all v_{iY} in the support of bidders' values, it holds*

$$v_{iY} > \max_{y\in\mathcal{A}_{-Y}} \sum_j v_{jy_j}.$$

When the values are strongly complementary at the top, no allocation involving strict subsets of Y yields higher welfare than the lowest individual value of the grand package among all bidders. Consequently, bidders essentially compete only on the grand package Y.[17] Define $v_{(j)Y}$ to be the realized j-th highest valuation for the grand package Y among the bidders. As above, $U_{it}(\beta, v; h_t)$ is the utility of bidder i from round t after history h_t when the values are v. Then,

Proposition 2 (Incremental Bidding Equilibrium in the Combinatorial Auction)**.** *Suppose valuations are strongly complementary at the top. Fix $\Delta > 0$.*

(i) For every $\epsilon > 0$, there is a finite constant $M > 0$ such that for all $m \geq M$, the incremental bidding profile $\beta^* = (\beta_1^*, ..., \beta_n^*)$ from Definition 3 satisfies

$$U_{i0}(\beta^*, v; h_0) + \epsilon \geq U_{i0}(\beta_i, \beta_{-i}^*, v; h_0),$$

for all value profiles v, all bidders $i \in \{1, ..., n\}$, and all feasible bidding strategies β_i.

(ii) In the limit $m \to \infty$, the resulting revenue is within Δ of $v_{(2)Y}$ almost surely. The valuation of the winner corresponds to $v_{(1)Y}$ almost surely.

The difference to the equilibrium statement in Proposition 1 for the single-good case is that, here, the strategies are not approximate best replies in all rounds t and after all histories h_t, but only at the outset of the auction (at $t = 0$). In the combinatorial auction, stage-wise ex-post mutual optimality does not hold because there can be histories in which some bidders have bid irrationally high on some smaller packages in the past, so that other

[17] The condition can be relaxed to allow for asymmetric valuations, provided the inequality holds for all v_{iY} in the support of at least one bidder i. In that case, the winner's valuation still coincides with the highest value for the grand package Y. Moreover, the resulting revenue remains within $\ell \cdot \Delta$ of the second-best allocation, since any such allocation comprises at most ℓ packages and bidders stop bidding one increment Δ below their respective values. The proof of Proposition 2 extends to this setting with only notational modifications.

bidders now face a coordination problem akin to the example discussed above, despite strong complementarity at the top.

3.3 Empirical Hypotheses

In both our laboratory and field settings, bidding is continuous — a process we model as the limit $m \to \infty$. Furthermore, because bidding increments are negligible relative to the total valuation of the goods, we treat Δ as practically zero.

The Candle Auction in the Field. The field data consists of combinatorial candle auctions for four goods subject to specific side constraints. Empirically, we observe that bidders almost exclusively target the "grand package" Y, which indicates a strong presence of value complementarities. Applying the logic of Proposition 2 to this environment, we propose the following:

Hypothesis 1 (Optimality in the Field)**.** *In the combinatorial candle auctions observed in the field, realized revenues correspond to the second-highest valuation for the grand package.*

Hypothesis 2 (Efficiency in the Field)**.** *The resulting allocations in the combinatorial candle auctions observed in the field are efficient.*

The Candle Auction in the Lab. Our experimental design utilizes combinatorial auctions with two goods and valuations that intentionally create a coordination problem. Unlike the field setting, we cannot rely on Proposition 2 for an equilibrium characterization. Instead, we compare the random-close rule against hard-close and soft-close benchmarks.

While the coordination problem persists across all rules, the random-close rule introduces a unique incentive to remain the standing high bidder throughout the duration of the auction. We expect this "threat of closure" to accelerate bidding dynamics and mitigate the coordination problem.

Hypothesis 3 (Bidding Dynamics in the Lab)**.** *Under the random-close ending rule, bidding escalates earlier than under the soft-close and the hard-close ending rules.*

Hypothesis 4 (Revenue and Efficiency in the Lab)**.** *Despite the random closing time, the candle auction achieves revenue and efficiency levels that are statistically no worse than those under the soft-close and hard-close rules.*

4 The Candle Auction in the Field

In this section, we analyze field data of candle auctions run between 2022 and 2024 on the blockchain networks Polkadot and Kusama. First, we provide some background on the underlying technology, followed by a detailed explanation of the auction rules. We then present summary statistics on all auctions, complemented by a qualitative report on some bid patterns.

4.1 Background

The Polkadot and Kusama networks are digital ecosystems that provide businesses and individuals with a secure and reliable way to store data and automate code execution using an append-only database, known as a blockchain. The networks are public and permissionless, meaning anyone can open an account and submit new data and instructions to be included in the blockchain.

The blockchain is redundantly stored on many servers in the network. These servers, known as validators, write the new data and instructions (often referred to collectively as transactions) on the blockchain by following a consensus protocol. For every new block, a validator is chosen to collect the newly entered transactions, verify their validity, and then distribute them to all other validators in the network. Once the block and its respective transactions receive the necessary number of attestations from the other validators in the network, all validators append the new block to their databases accordingly. If followed by every node in the network, the consensus mechanism thus guarantees that each node has an identical copy of the blockchain at any point.[18]

An instructive example of this process is a user submitting the instructions to transfer some of her tokens from account A to account B. Upon submission, the validator tasked with building a new block checks whether the user is the actual owner of the tokens of account A and that the requested transfer does not exceed her balance. After verifying that these conditions are met, i.e., the transaction is valid, the validator includes it into a block (potentially with many other transactions by other users) and then distributes the block to the network. The other nodes then again check the instructions in the block, send their attestations, and after receiving enough attestations from other nodes, add the block to their own copy of the blockchain. Such a transfer is only a simple example; yet, more complex transactions are also possible, where actions can be triggered conditionally based on other events, or entire blocks of code can be executed. By now, there are many use cases, including decentralized finance (DeFi), supply-chain management, gaming, and digital identity systems (see Halaburda et al., 2022, for an introduction).

The consensus process is relatively time-intensive. Moreover, there are resource-intensive cryptographic safeguards in place that protect the network and its blockchain from potential attacks. Together, they imply that the bandwidth of available data storage space in a block (also known as blockspace) is severely limited, which raises the question of how to allocate it best. While most blockchains from earlier generations, such as Bitcoin and Ethereum, sell their storage space on a per-block basis, Polkadot offers blockspace with fixed bandwidth for long-term periods in combinatorial candle auctions, which we describe next.

[18]For readers interested in this topic, Gans (2023) provides a (economic) introduction to the consensus problem in blockchains. For (more technical) discussions of Polkadot's particular solution, see Burdges et al. (2024) and Cevallos and Stewart (2021).

4.2 Description of the Auctions

We consider data from 70 auctions held between June 2022 and August 2024 on the Polkadot and Kusama networks.[19] To participate in these auctions, bidders were required to have a valid account on the respective blockchain and place their bids using the network's native tokens (DOT or KSM). Participants could acquire these tokens beforehand on various exchanges or from brokers. The goods being sold in a single auction in Polkadot (Kusama) consisted of eight lease periods, with each lease period lasting 12 (6) weeks, resulting in a total duration of approximately two (one) years. Bidders could submit bids on any combination of these lease periods, with the only side constraint being that the lease periods must be connected.

Each auction lasted roughly seven days (or 99000 blocks, the unit of time that the blockchain uses), divided into *two phases* (see Figure 1). The first, termed the *starting phase*, lasted 45 hours (27000 blocks) and served as a grace period during which bidders could finalize preparations, secure funding, and start bidding. The second phase, known as the *ending phase*, followed thereafter and lasted for 120 hours (72000 blocks). The submitted bids were continually written on the blockchain and publicly observed throughout the auction. The ending time of the candle auction, determined retroactively after the auction concluded, corresponded to a specific block appended during the ending phase. This ending time was uniformly distributed throughout the ending phase, a fact that was public knowledge and verifiable by all participants, due to the transparent nature of the open-source code

[19] In total, 219 auctions were held on Polkadot and Kusama between November 2021 and August 2024, after which Polkadot and Kusama adopted a different approach to selling blockspace. Restricting the auctions for our analysis is necessary for two reasons. First, some auctions had no or only one bidder. Second, some auctions featured so-called "crowdloans"—bidding mechanisms where a group of users collectively contributes to a single account, which then automatically places bids on their behalf and pays out predefined rewards in case of winning, thus substantially changing the nature of the game. Nevertheless, including these auctions in our analysis does not significantly affect our results, and we report them in other footnotes.

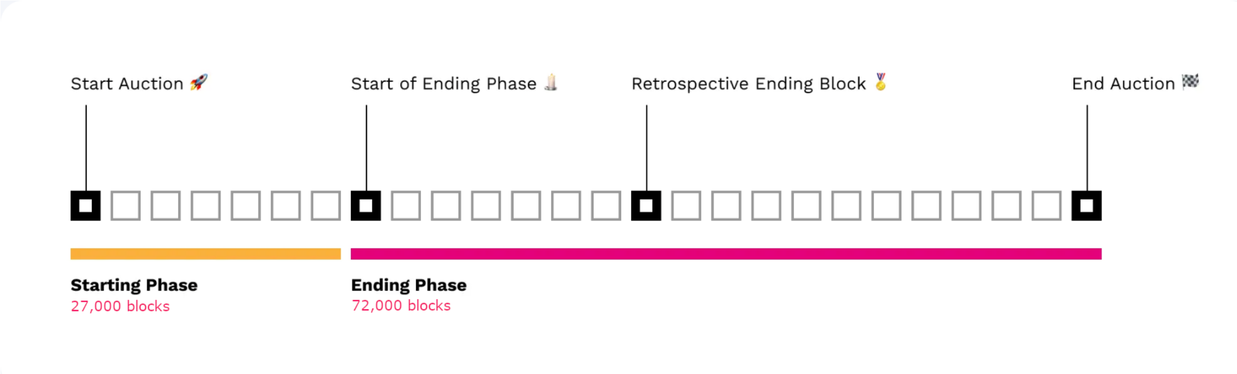

Figure 1: Schematic depiction of the two phases in candle auction.
Note: The "Starting Phase" was meant for bidders to prepare their bids. While bidding was allowed during the whole auction, the ending time was uniformly distributed on the "Ending Phase" and determined retroactively, i.e., after the auction ended.

on the blockchain.

The auction winners were the bidders whose combination of bids generated the highest revenue at the retroactive (random) ending time. In the event of a tie, priority was given to the earliest of the winning allocations. In case of multiple earliest winning allocations, one of them was chosen randomly. In case no bids had been entered at T, no one received anything. Winning bidders funded their bids by locking the respective amount for the of the winning package, rendering them unusable during this time. Upon the lease's conclusion, the locked amount was released. Consequently, the cost of bidding was not the bid itself, but the opportunity cost incurred by locking the tokens. As a reference, the Polkadot network paid users who *staked* their tokens an interest of roughly 20% p.a., which allows to estimate the actual cost of a bid.[20] For simplicity, we nevertheless refer to the face value of the winning bids as the auction's revenue in the following.

[20] Polkadot and Kusama employ a proof-of-stake consensus mechanism. Staking refers to the process of locking tokens in order to participate in the consensus mechanism. Similarly to mining in proof-of-work mechanisms, contributing to the network's security is remunerated with so-called staking rewards (cf. Gans, 2023).

Auctions on Polkadot	**Min**	**25%**	**Median**	**Mean**	**75%**	**Max**
No. of Bidders per Auction	2.0	2.0	3.0	3.5	5.0	7.0
No. of Submitted Bids per Auction	2.0	5.0	11.0	18.5	24.0	66.0
Full Lease Bid Share (in %)	22.2	58.9	78.6	73.7	94.7	100.0
Lockup Value (in USD)	694	1663	13879	46612	73703	167598
Relative Revenue (in %)	1.5	86.9	100.0	83.9	100.0	100.0
Efficiency (in %)	60.5	100.0	100.0	97.4	100.0	100.0
Auctions on Kusama	**Min**	**25%**	**Median**	**Mean**	**75%**	**Max**
No. of Bidders per Auction	2.0	2.0	2.0	2.5	3.0	5.0
No. of Submitted Bids per Auction	2.0	3.0	5.0	8.0	11.5	31.0
Full Lease Bid Share (in %)	0.0	18.3	50.0	50.6	74.9	100.0
Lockup Value (in USD)	0	440	2606	12177	9614	159926
Relative Revenue (in %)	0.0	69.0	100.0	77.7	100.0	100.0
Efficiency (in %)	0.0	100.0	100.0	89.9	100.0	100.0

Table 1: Summary statistics of the Polkadot ($N = 15$) and Kusama ($N = 55$) auctions.
Note: "Full Lease Bid Share" describes the share of bids for the grand package containing all available lease periods. Relative Revenue is defined as the ratio between the amount of the winning bid combination and the amount of the bid combination that would have won at the very end of the auction. Efficiency is defined as the ratio between the highest bid combination of the winner and the amount of the bid combination that would have won at the very end of the auction.

4.3 Results

Table 1 provides summary statistics for the auctions on Polkadot and Kusama separately. Our sample consists of 70 auctions (15 on Polkadot and 55 on Kusama), with winning bids (lockup value) accumulating to 1.38 million USD. Across all auctions, the winning bids averaged around 19555 USD, with approximately 2.7 unique bidders per auction submitting around 10 bids in total. The last two rows describe crucial properties of the auction outcomes that we want to discuss in the rest of this section.

4.3.1 Revenue

An immediate consequence of the random-close rule of the candle auction is that the realized revenue in an auction is lower than the revenue that would have accrued from the last submitted bids in the auction. To illustrate this, Figure 2 shows the bid paths in an auction for the package containing all available lease periods (the "grand" package), which was the most competitive package and ultimately became the only package in the winning allocation.[21] Here, the retroactive ending block (indicated by the red dashed line) was drawn to be in the first half of the ending phase, so that the winning bid (1288 USD) was considerably lower than the final bid (1640 USD). On the other hand, we would expect the random-close rule to create pressure on bidders to escalate their bidding early in the auction. Such an effect is also visible in Figure 2, where the ending phase starts with relatively high bids.

To understand the net effect of these two forces, we calculate the relative revenue share in an auction as the ratio between the amount of the winning bid combination and the amount of the bid combination that would have won at the very end of the auction. Across all the auctions, the relative revenue share amounts to 79%.[22] Figure 3 illustrates the distribution of the relative revenue (in %) for Polkadot and Kusama, respectively.

All in all, the loss through the random-close rule is relatively small and the distribution of revenues is concentrated at the top. As shown in Section 3, this is what theory would predict. In Section 5.3, we will see that it also agrees with the experimental findings.

4.3.2 Efficiency

The possibility of an early auction ending may also hamper efficiency. Of course, we do not know the true valuation of a bidder for a package, but we suggest a proxy: the last bid submitted by the bidder. This allows us to compute the welfare-maximizing combination of packages and compare the corresponding welfare to the welfare under the winning packages, giving us a measure for the auction's efficiency.[23]

To illustrate, we may consider Figure 4, which shows the bid paths on the largest package

[21] In the majority of the auctions, the grand package, which contained all lease periods, was the most competed-for and ended up being the only package in the winning allocation (cf. the Full Lease Bid Shares in Table 1 and the discussion in the section on combinatorial outcomes below).

[22] Across all 219 auctions, the relative revenue share amounts to 84.6%. See Footnote 19 for more information.

[23] Our theoretical results in Section 3 suggest that for all but the highest bidder, this proxy is suitable, and our metric provides an upper bound for the efficiency of the auction.

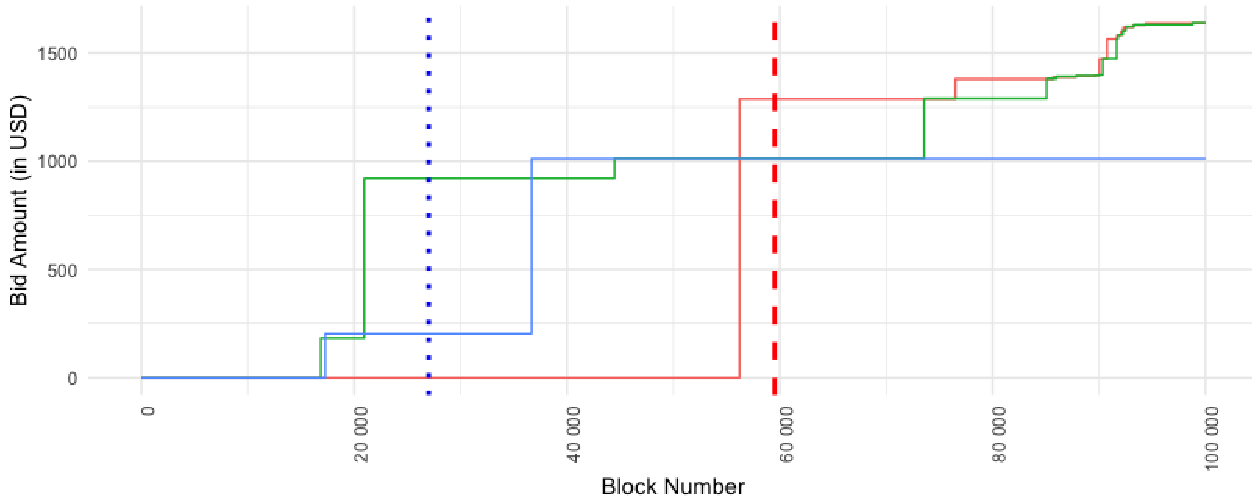

Figure 2: Bid dynamics in auction 107 on Kusama (for the grand package involving all available lease periods). Relative revenues are low but efficiency is high.
Note: The dotted blue line: start of ending period; red dashed line: randomly chosen ending time.

in Polkadot's 78th auction, which was the only package in the winning allocation. Although relative revenue was suboptimal (73.8%), this auction was, according to our criterion, 100% efficient, because the bidder with the red bid path was leading both when the auction closed and at the random end time.

On the other hand, Figure 5 illustrates an auction that yielded an inefficient outcome. Here, the bidder with the red bid path on the largest package won the auction. Yet, welfare would have been maximized by allocating the good to the gray bidder, who unknowingly started bidding only after the auction was already closed and significantly outbid the others at the end. This resulted in low relative revenue (22.5%) and comparatively low efficiency (60.5%).

Across all auctions, we find an average efficiency of 91.5%.[24] (Table 1 provides more details on the distribution.) In other words, the bidder with the highest bid at the end often

[24]Across all 219 auctions, the average efficiency is 92.2%. See Footnote 19 for more information.

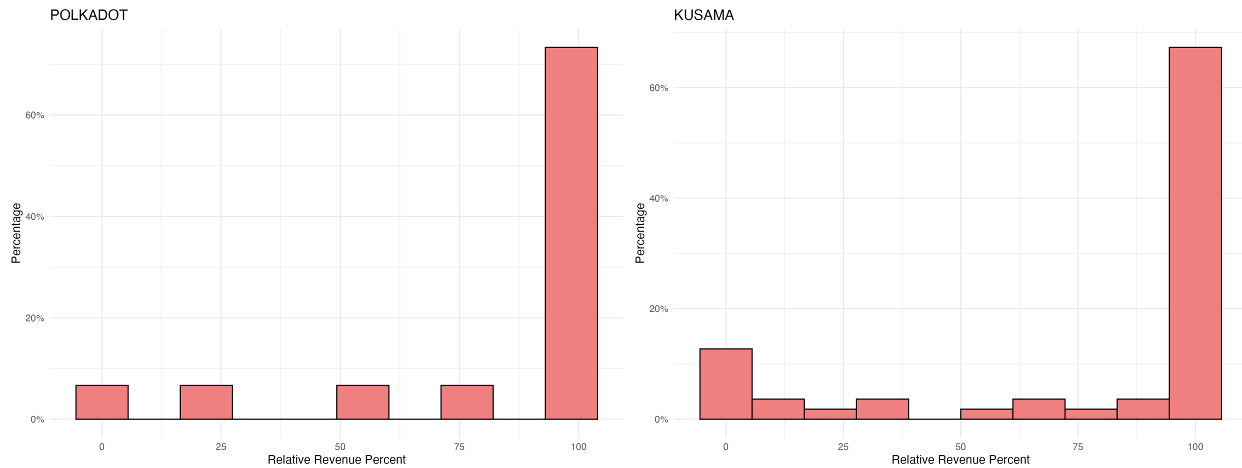

Figure 3: The histogram depicts the distribution of relative revenues across auctions on Polkadot and Kusama.
Note: Histogram for Polkadot on the left; histogram for Kusama on the right.

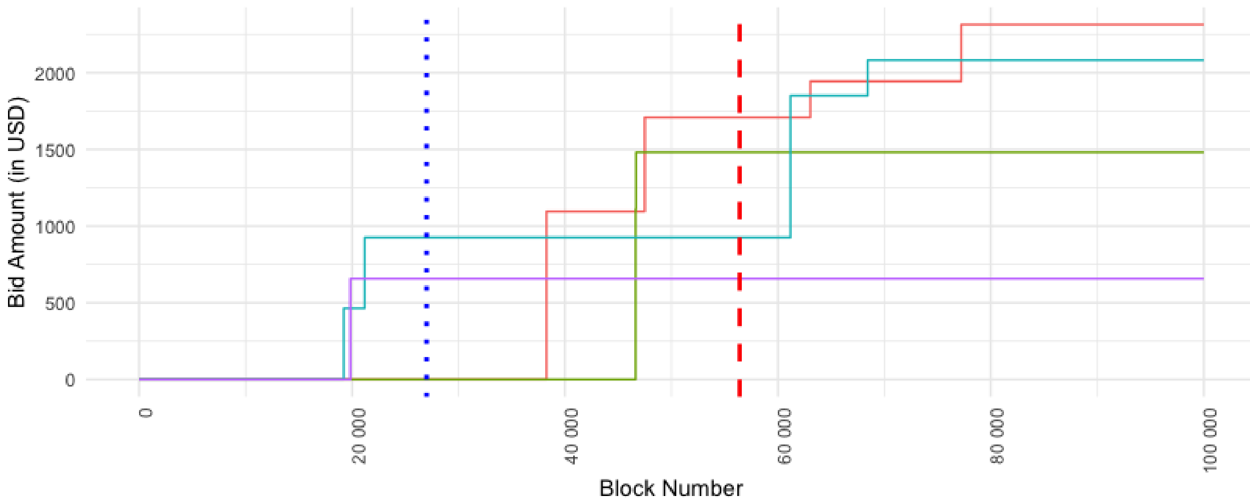

Figure 4: Bid dynamics in auction 87 on Polkadot (for the grand package). Relative revenues are low but efficiency is 100%.
Note: The dotted blue line: start of ending period; red dashed line: randomly chosen ending time.

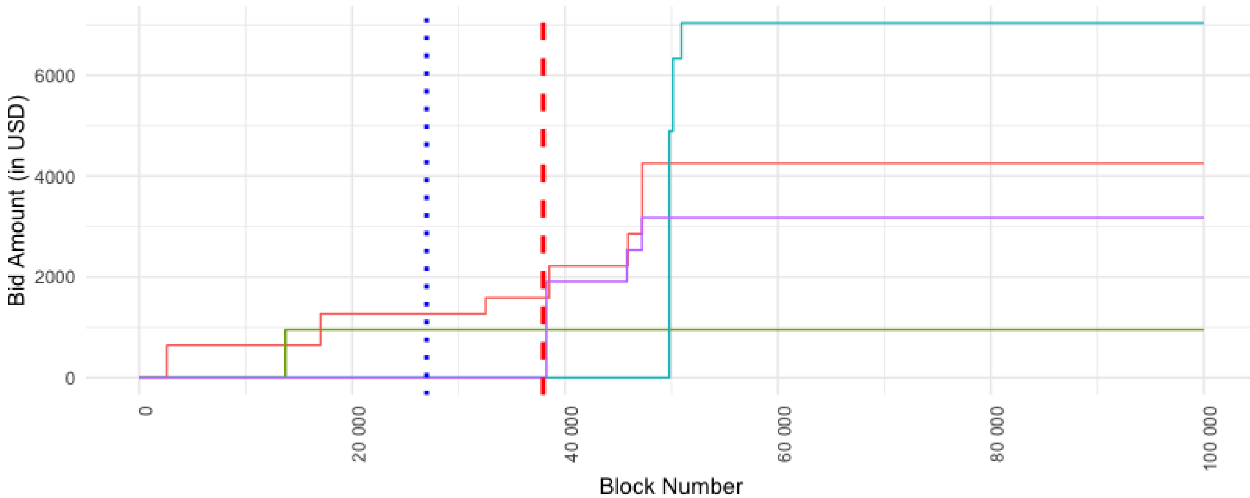

Figure 5: Bid dynamics in auction 72 on Polkadot (for the grand package). Relative revenues and efficiency are low.
Note: The dotted blue line: start of ending period; red dashed line: randomly chosen ending time.

led the bidding during the retroactive ending time.

4.3.3 Combinatorial Outcomes

The majority of auctions had most bidders competing for the full duration of the lease and partial bids (an average of 26.3% in Polkadot and 49.4% in Kusama; cf. Table 1) were mostly irrelevant to the auction outcomes, so that the final allocations hardly ever consisted of multiple winners. There are, however, four exceptions, two in Polkadot and two in Kusama. In all four auctions, there were three unique bidders, high efficiency (99.9%), and high relative revenue (89.9%).

With multiple packages in the winning allocation, a graphical representation of the bidding dynamics is not straightforward. In the following, we thus provide a qualitative description of the bidding dynamics in these four auctions to offer the reader a better understanding of how the results were determined.

1. **Auction 61 on Kusama**: In the initial phase, Bidders A and B incrementally competed for the package of lease periods 2-8. Approximately two days later, Bidder C entered the auction by bidding on lease period 1, thereby complementing the packages of A and B. This pattern suggests the possibility of back-channel *communication* among A, B, and C prior to the auction, as such an interaction would explain why both original bidders initially excluded lease period 1. Consequently, one of the initial bidders and Bidder C ultimately won the auction. Efficiency and relative revenue were above 99.5%.

2. **Auction 67 on Polkadot**: This auction exhibited a notably strategic bidding dynamic. In the early stages, Bidder A repeatedly increased bids on the package of lease periods 2–8 (from \$760 to \$76,057) even in the absence of direct competition. On the second day, Bidder B entered by outbidding A with a \$114,085 bid on the largest package (of lease periods 1–8). Later the same day, Bidder C joined by placing a bid on lease 1, effectively aligning with A. While this coordination could reflect back-channel communication between A and C, it may also be explained by A's escalating bids serving as a public signal, inviting a complementary bidder on lease 1. Moreover, A's willingness to increase bids without public competition suggests the anticipation of B's eventual participation, hinting at a secondary interaction occurring outside the formal auction process. Ultimately, A and C successfully outbid B, achieving 100% efficiency and paying their final, highest bids (i.e., 100% in relative revenue).

3. **Auction 69 on Polkadot**: Unlike the previous examples, the first bid submitted targeted lease period 1 (Bidder A), which was followed two days later by a complementary bid from Bidder B on the package containing lease periods 2–8. Subsequently, Bidder C, apparently unable or unwilling to split the lease, entered the auction with a bid for the the largest package (of lease periods 1–8), though ultimately without surpassing the combination of A and B. While the auction achieved 100% efficiency,

late-stage bidding escalations yielded a relatively lower revenue, with the final value of approximately 59.9%.

4. **Auction 128 on Kusama**: In this auction, Bidders A and B initially competed for the full lease duration (1–8). Observing that B's bids surpassed her bids, A submitted a new bid for lease period 1, presumably acknowledging that she is not competitive, signaling an interest in partnering with another bidder for the package with lease periods 2–8, and demonstrating flexibility in using a lease period. A short time after that, Bidder C joined with a bid on the package with lease periods 3–8, thus aligning with A. As a result, A and C ultimately prevailed over B, achieving both complete efficiency and maximum relative revenue.

4.3.4 Conclusion

The field data demonstrate that the candle auction, perhaps surprisingly, performs quite well on our measures of revenue generation and efficiency. We take these findings as strong evidence for our Hypotheses 1 and 2.

While there is a theoretical risk of low revenue and efficiency if bidders fail to engage in early bidding, this concern rarely materializes in practice. To illustrate this point, Figure 6 presents the average relative winning bid over the duration of an auction. This metric illustrates how quickly bidders escalated their bids toward the maximum bid observed in each auction. As we can see from the graph, the average relative winning bid is already around 25% of its respective maximum at the end of the grace period and above 81% half way through the ending phase, where bidders would expect the end of the auction.

While our field data provide robust empirical evidence for the effectiveness of the candle auction, a fundamental challenge remains in assessing its efficiency: the inability to directly observe bidder valuations. To address this limitation, we designed an experiment that allows us to induce values and compare the candle auction to other auction formats.

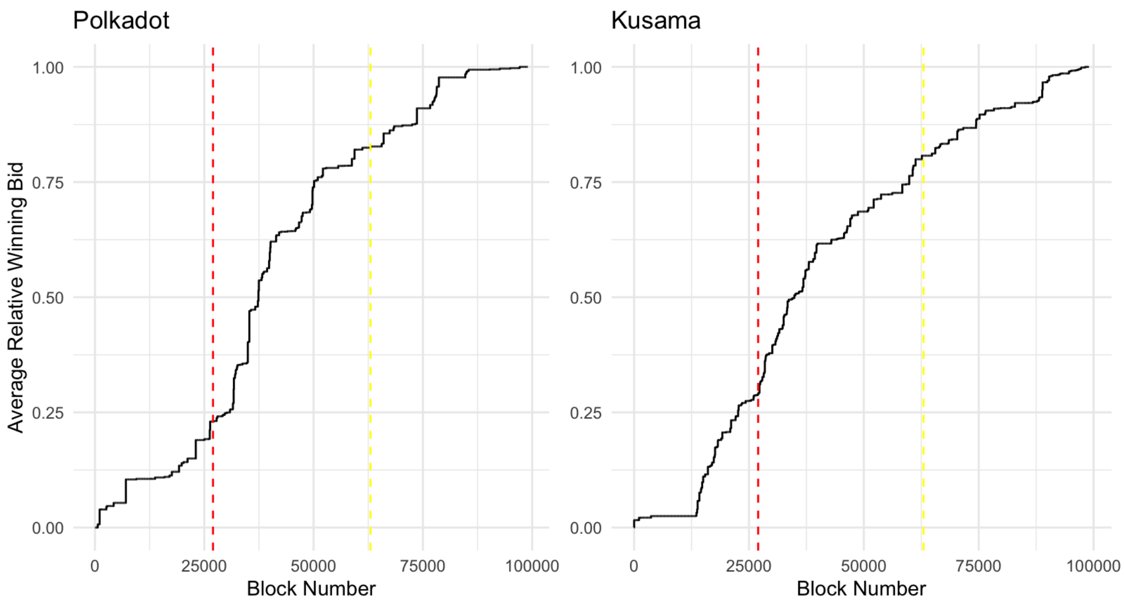

Figure 6: Average relative winning bids on Polkadot and Kusama.
Note: For each auction, the variable is defined as the ratio of the currently winning combinatorial bid to the highest winning bid observed in the auction. We calculate this ratio for each point in every auction (i.e., running maximum) and then take the average across all auctions. The dashed red line indicates the end of the grace period and the dashed yellow line indicates half of the duration of the ending phase.

5 The Candle Auction in the Lab

5.1 Experimental Design

We designed our experiment to replicate some key features of the candle auctions from the field. In particular, we incorporated combinatorial aspects and communication among bidders. As mentioned in the introduction, we think the latter is a key feature of most online communities, where communication is cheap, instantaneous, and unobservable to outsiders. Further, we compare the candle auction to other commonly used closing rules in auctions.

Specifically, we study ascending combinatorial auctions in which the items for sale are the "right of use" of a fictional good for two "periods", $\{1, 2\}$, which are sold in three "packages" $\{\{1\}, \{2\}, \{1, 2\}\}$. Bids must exceed previous bids on the respective package and be integer values. The winning bids are selected to maximize total revenues, i.e., the bid for package $\{1,2\}$ is winning if it is higher than the sum of the bids for packages $\{1\}$ and $\{2\}$, and vice versa. In the event of a tie, priority is given to the earliest of the winning allocations. In case of multiple earliest winning allocations, one of them is chosen randomly. If no bidder submits a bid, no one receives anything. The payment rule is first-price; i.e., winning bids must be paid.

We want to compare three ending formats: (1) the candle format, (2) a hard-close rule, and (3) an soft-close rule. In a hard-close rule auction, bidders can freely submit increasing bids, and the auction ends after 60 seconds. In the candle auction, the auction's ending time is determined retroactively; i.e., bids on packages are accepted for 60 seconds. However, the actual ending time of the auction is chosen randomly between seconds 20 and 60. In the soft-close rule format, the ending time is determined endogenously. Specifically, the auctions run for at least 45 seconds. Any bid made in the last 10 seconds resets the timer to 10 seconds, so the auction ends only if there are no new bids within the last 10 seconds. In all auctions, the time remaining in the auction is shown graphically by a shrinking bar (see Fig. 13 in Online Appendix B).

In every auction, three bidders will be active. Bidders can have one of two roles that are commonly known when entering the auction: (1) flexible bidder, (2) inflexible bidder. There will be one inflexible bidder and two flexible bidders in every auction. The inflexible bidder has a positive valuation only for the grand package, $\{1,2\}$. The flexible bidders hold valuations for the individual packages that add up in case they win the grand package. Specifically, the inflexible bidder draws a valuation v from the uniform distribution on $[45,55]$ for the package $\{1,2\}$ and always holds a valuation of zero for the packages $\{1\}$ and $\{2\}$. On the other hand, flexible bidder $f=1,2$ draws a valuation v_f for $\{1\}$, implying that she values item $\{2\}$ at $40-v_f$ and package $\{1,2\}$ at 40. The values v_f are drawn independently from a uniform distribution on $[0,40]$. Table 2 summarizes the value model.

Under this value model, it is efficient for the inflexible bidder to obtain the grand package whenever $v \geq \max\{40-v_1+v_2, 40-v_2+v_1\} = 40+|v_1-v_2|$ and for the two flexible bidders to each receive one of the items otherwise. However, to win against the inflexible bidder,

	Package		
	$\{1\}$	$\{2\}$	$\{1,2\}$
Inflexible Bidder	0	0	$v \sim U[45, 55]$
Flexible Bidder 1	$v_1 \sim U[0, 40]$	$40 - v_1$	40
Flexible Bidder 2	$v_2 \sim U[0, 40]$	$40 - v_2$	40

Table 2: Table of the bidders' values.
Note: In each auction, there is one inflexible bidder that only values the package $\{1, 2\}$ and two flexible bidders with (additive) values for the packages $\{1\}$ and $\{2\}$.

the flexible bidders must coordinate their bids accordingly. For simplicity, we did not allow bidders to bid above their value on a package.

We offer two channels of communication. First, a public chat where all three players can send and read messages. Second, a private chat between the two flexible bidders, where the inflexible bidder cannot write or read. The public chat theoretically allows all players to coordinate their bidding across the different auctions, while the private chat allows the two flexible players to coordinate against the inflexible player. Chat sessions are available only before every auction begins and are closed before the auction starts.

5.2 Experimental Procedure

At the start of the experiment, participants were randomly assigned to one of three auction formats and given instructions on the specific rules. Each participant learned their role as either a flexible or inflexible bidder, which remained constant throughout. In each auction, groups consisted of two flexible and one inflexible bidder. Every group played 10 payout-relevant rounds in the same group composition. Before these rounds, participants completed three trial rounds to familiarize themselves with the game and interface. Groups were reshuffled after the trials to prevent any agreements or experiences from influencing the paid rounds. Bidders' valuations were independently determined for each auction. The procedure for a round was a follows. First, new values (v, v_1, v_2) for the individual packages were drawn and shown to the respective bidders. Then, all participants entered the commu-

Total Number of Bidders	162
Total Number of Groups	54
Total Number of Auctions	540
Number of Candle Groups	18
Number of Soft-Close Groups	18
Number of Hard-Close Groups	18

Table 3: Summary of experimental data

nication phase (see Figure 12). This stage lasted either 45 seconds or until all participants indicated that they were ready to proceed.

After that, the auction started, and subjects could submit bids. Given that the allocation rule in the auction, namely selecting as winning bids those that maximize revenues, is probably not easy to understand initially, we included one important feature to simplify bidding. When subjects selected a package to bid on, a message was visible telling them the minimum bid they had to place on this package to become the currently leading bid (possibly together with the bid on the other package). The bids could then be entered by a slider or by entering the bid directly in a window. For a visual representation of the screen, see Figure 13 in Online Appendix B.

After the end of each auction, participants received feedback on the final winning bids and the allocation of packages (see Figure 14 in Online Appendix B). In addition, subjects in the candle auction format were informed about the realization of T and the respective snapshot of winning bids at that time. Profits for this round were calculated and shown to the subjects.

For payment, we randomly selected one auction round and subjects were paid their earnings for this round in cash. In addition, there was a show-up fee of €15. Payments ranged from €15 to €123, with an average of €26.20 for an average duration of about 60 minutes.

The experiments took place in January 2023 in the AWI Lab at the University of Heidelberg, mostly with undergraduate students of all fields. In 14 sessions, 162 subjects took part in total. This yielded 18 groups of 3 bidders for each treatment. The experiment was computerized using oTree (Chen et al., 2016). At the beginning of each session, subjects were randomly placed in different cubicles of the lab where they were asked to read the instructions. Instructions on paper were distributed, followed by a short comprehension quiz (see the Online Appendix for instructions and quiz). Once all subjects solved the quiz correctly and there were no more questions, the experiment started with 3 practice auctions, followed by the actual 10 auction rounds. Ultimately, a brief questionnaire was administered, requesting information on gender and field of study. The sessions were conducted in German. English translations of the instructions and the comprehension quiz are available in Appendices E. Table 3 provides an overview of the data we collected in our experiment.

5.3 Experimental Results

In this section, we analyze the experimental data. We first present our main result on revenues and efficiency. Then we analyze the chat protocols and discuss collusion. Last, we report some findings on the timing of bids and the combinatorial aspects of the auctions.

5.3.1 Revenues and Efficiency

The histogram in Figure 7 and Table 4 (column 1) show the efficiency of all three auction formats in the experiment, where again efficiency is measured as the percent of potential surplus that is realized by the winning bids. Overall average efficiency is about 93% and there is clearly no significant difference across treatments (MWU-tests, with $p > 0.23$).[25]

The second column in Table 4 shows that about 60% of auctions are fully efficient (i.e. the winners are the ones with the highest values). The occasional inefficiencies seem to be primarily because the inflexible bidders win too often. For the randomly generated values in our experiment, inflexible bidders should win no more than 45% of the auctions. However,

[25]Throughout, we use two-sided tests with groups as independent observations

	efficiency	% efficient	relative revenues	collusive
Hard	0.928	0.583	0.732	0.072
Soft	0.933	0.661	0.649	0.239
Candle	0.934	0.633	0.690	0.033

Table 4: Auction Results by Treatment.
Note: Column efficiency shows average efficiency; % efficient shows the share of auctions with a fully efficient outcome; relative revenues is the ratio of actual revenues relative to the theoretically expected revenues; collusive is the share of auctions in which the chat was coded as collusive (see Section 5.3.2).

they actually won about roughly 50% of the auctions in all treatments (for more on this, see the subsection on Combinatorial aspects below).

The third column in Table 4 and Figure 8 report relative revenues, which are defined as the ratio of the actual revenues relative to the theoretically expected revenues (i.e., value of second-best package plus 1 bidding increment). While the hard-close auction seems to generate the highest relative revenues, in fact, the differences are not significant for any of the pairwise treatment comparisons (MWU-tests, $p > 0.41$).

Thus, we can state our first main experimental result.

Result 1 (Revenues and Efficiency)**.** *Candle auctions, on average, do not yield lower efficiency or revenues than the hard-close or soft-close auctions.*

This result seems to directly confirm our Hypothesis 4. Yet, one very noticeable feature of Figure 8 is the high frequency of revenues close to zero, particularly in treatment Soft and to a lesser extent in treatment Hard. (Relative) revenues close to zero make it very likely that bidders have colluded, a topic to which we turn next.

5.3.2 Communication and Collusion

To examine how subjects managed to collude, we study the content of the chat. We coded the chat logs between players for each auction with two dummy variables (coll_global, coll_local). The first, coll_global, is 1 if participants in the public chat attempted to motivate the other player(s) to reduce the final price in the auction, and the other players responded positively

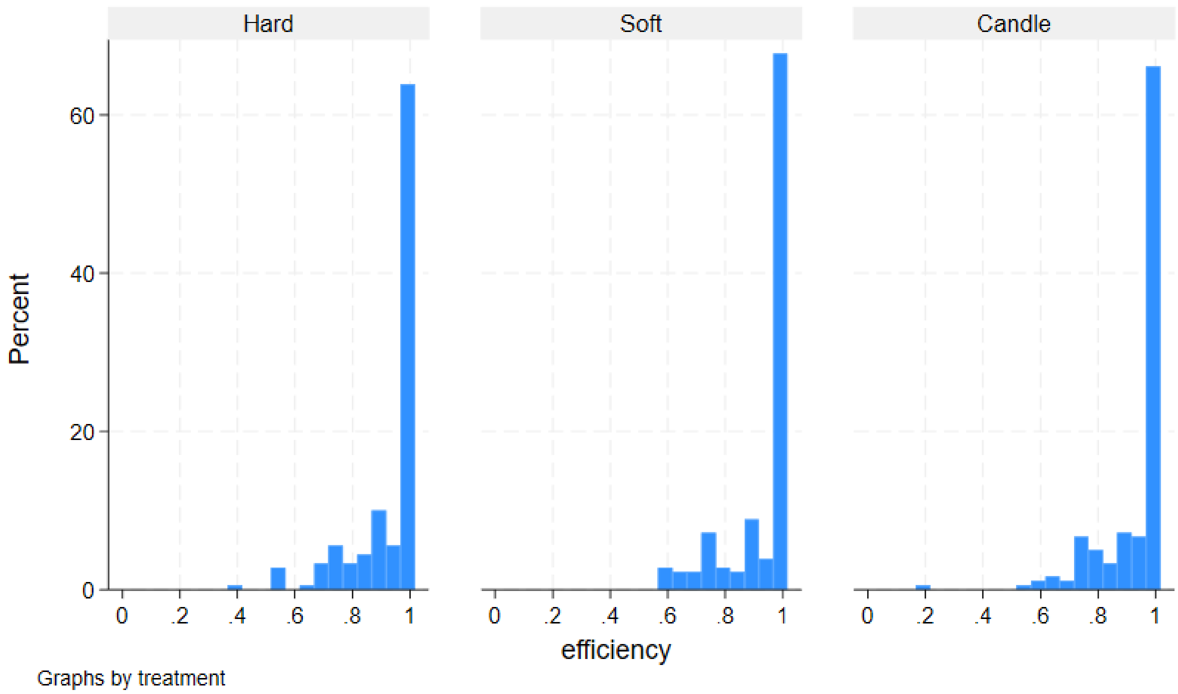

Figure 7: Histogram of efficiency in experimental auctions.
Note: The plots show histograms of relative efficiency for each treatment (Hard, Soft, Candle).

to that attempt. Similarly, coll_local is one when such a joint collusion effort was made in the private chat.[26]

In many of the chats, the subjects explicitly agreed on taking turns winning the auctions. Examples of collusive (global) chat messages we found are:

- "Okay, hear me out: we can maximize the payouts by overbidding each other as little as possible. If we theoretically take turns and let the other party win the auction at

[26]Two research assistants were asked to code chat conversations as "successful in agreeing to collude". In the instructions to the RAs, collusion was defined as "an agreement aimed at lowering the auction price - sometimes almost to a price of 1 point. Any agreement where bidders promise to bid less than their valuation would be considered collusive. It would also be typical for bidders to agree among themselves on who gets to 'buy cheaply' in which auction." The two research assistants independently coded the chats. In cases where their assessments did not align, a third research assistant, unaffiliated with the original research team, was brought in to resolve discrepancies. This is one of the standard ways of coding chat in experimental economics, see Brandts et al. (2019).

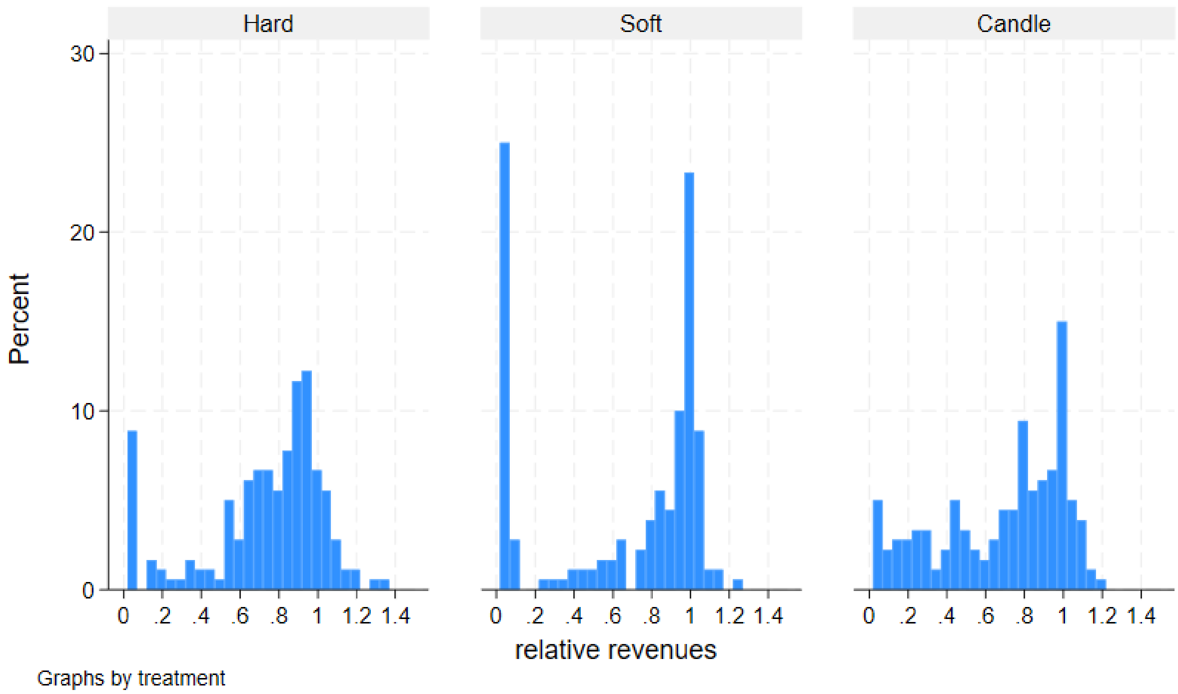

Figure 8: Distribution of relative revenues in the three treatments.
Note: The plots show histograms of relative revenues for each treatment (Hard, Soft, Candle).

the minimum bid, we essentially have a 50-50 chance at a big payout in the end."

- "Should we agree with Bidder 1 that they get the next round, and we take this one?"
- "Maybe let them have this round, and they'll let us have the next two?"
- "Let's arrange it so that only one person bids per round. That way, everyone wins every third round."
- "I think it makes sense not to keep driving each other's bids higher and instead let one player win each time."
- "It's been an honor bidding with you all."

The fourth column of Table 4 shows the frequency of collusive global chats (coll_global = 1). While less than 4% of chats are coded as collusive in the Candle auctions, almost 24% of chats are coded as collusive in the Soft auctions. This difference is significant (MWU-test,

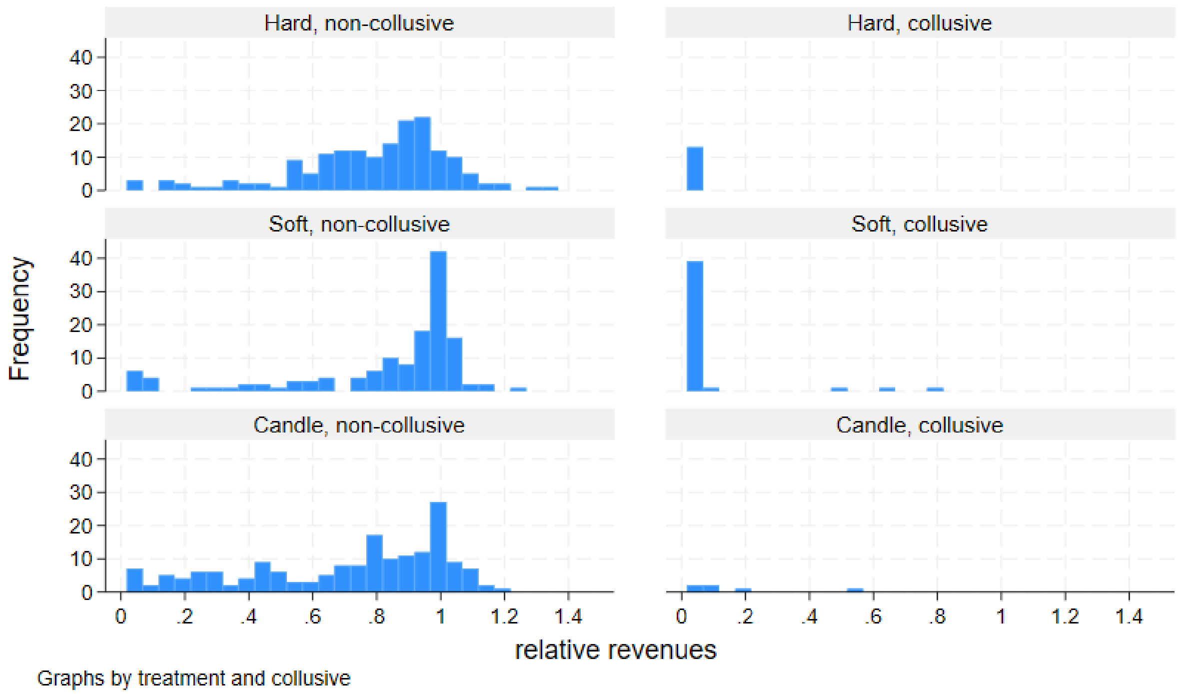

Figure 9: Revenues with and without collusion.

Note: The plots on the left show histograms of relative revenues in the auctions coded as *non-collusive* for each treatment (Candle, Soft, Hard). The plots on the right show the histograms for the auctions coded as *collusive*, respectively.

$p = 0.014$). The hard-close auction is between the two others, not significantly different from Candle but significantly less collusive than Soft ($p = 0.046$).

To see that chat is actually causal for collusion, we split auctions which were coded as collusive versus those that were not. Figure 9 shows relative revenues for the respective auctions across the three treatments. In treatments Soft and Hard close, more than 80% of auctions with collusive chat yield relative revenues of very close to zero. In candle auctions, there are very few instances of collusive chat to start with, and even in those, relative revenues are not always close to zero.

Table 5 provides further evidence. In the OLS regressions with standard errors clustered on the group level, relative revenue (in %) is regressed on treatment dummies, the dummy for a (globally) collusive group (coll_global), and their interaction terms. Specification (1) reiterates our finding above that, without further controls, relative revenues are equal across

	relative revenues		
	(1)	(2)	(3)
(constant)	0.690***	0.771***	0.708***
	(0.054)	(0.027)	(0.049)
Soft	-0.041		0.123**
	(0.097)		(0.061)
Hard	0.042		0.079
	(0.084)		(0.065)
coll_global=1		-0.701***	-0.540***
		(0.032)	(0.093)
Soft × (coll_global=1)			-0.221**
			(0.101)
Hard × (coll_global=1)			-0.226**
			(0.103)
Num.Obs.	540	540	540
R^2	0.009	0.402	0.422

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 5: Determinants of relative revenues. OLS results.
Standard errors in parentheses are clustered on the group level. Soft and Hard are treatment dummies; coll_global is a dummy which is 1 if the auction was coded as collusive.

treatments. Specification (2) shows that collusive agreements indeed result in lower revenues. Specification (3) ultimately demonstrates that collusion agreements under the soft-close rule and the hard-close rule result in significantly lower revenues compared to the candle auction.

Result 2 (Collusion)**.** *Collusion agreements are less prevalent in the candle auction (3.3% of all auctions) than under the soft-close rule (23.9%) and the hard-close rule (7.2%). In the latter two, collusion is usually successful, reducing revenues by as much as 20% relative to the candle auction.*

5.3.3 Delayed bidding in Candle Auctions

While candle auctions seem to be more robust to collusion, we have seen above that on average revenues are not significantly different from the other auction formats. An explanation

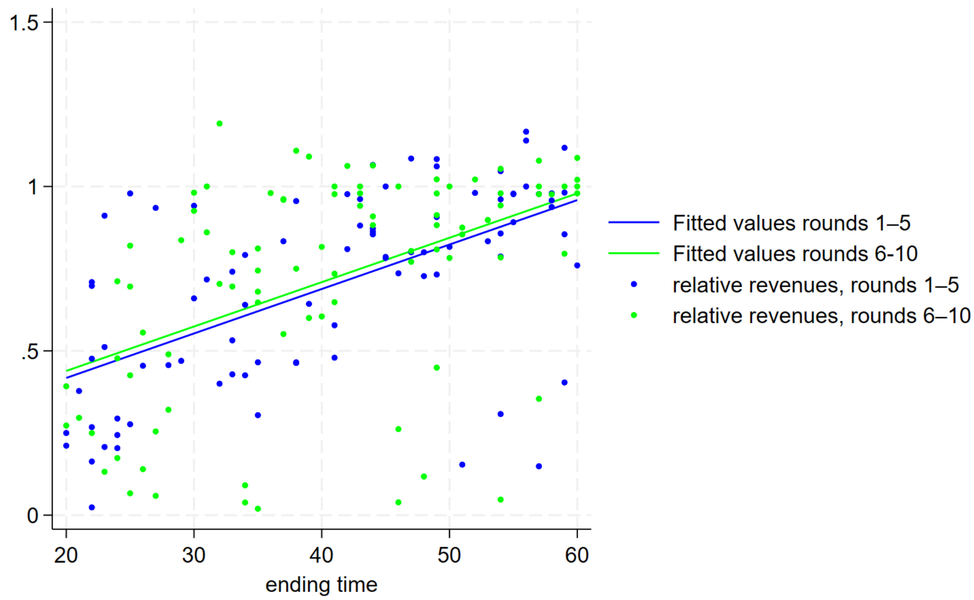

Figure 10: Relative Revenues (i.e., effective revenue divided by the value of the second-most-valuable allocation) is positively related to the ending time in the 180 candle auctions, suggesting that low observed revenues can be explained by an early ending time.
Note: Each dot represents revenues from one auction.

for this can be seen in the lower left panel of Figure 9. There are some auctions in treatment Candle where chat was not collusive but revenues were rather low anyway. Figure 10 shows a scatter diagram of ending times and revenues. If bidders follow the incremental bidding strategy, bids should reach the maximum right after the begin of the ending phase. Thus, the relationship between ending time and revenue should be flat. However, Figure 10 shows a positive and significant influence of ending time on relative revenues ($p < 0.001$ from an OLS regression with standard errors clustered by group). This relation seems stable over time as there is hardly a difference between the first 5 and the last 5 rounds.

Another way of looking at the timing of bids is to calculate the currently highest relative bid combination as the sum of bids on the package that would win the auction if it ended in this moment divided by the value of the second-most-valuable allocation. Incremental bidding would imply that the currently highest relative bid combination becomes 1 right at the start of the ending phase. Figure 11 depicts the average of currently highest relative bid

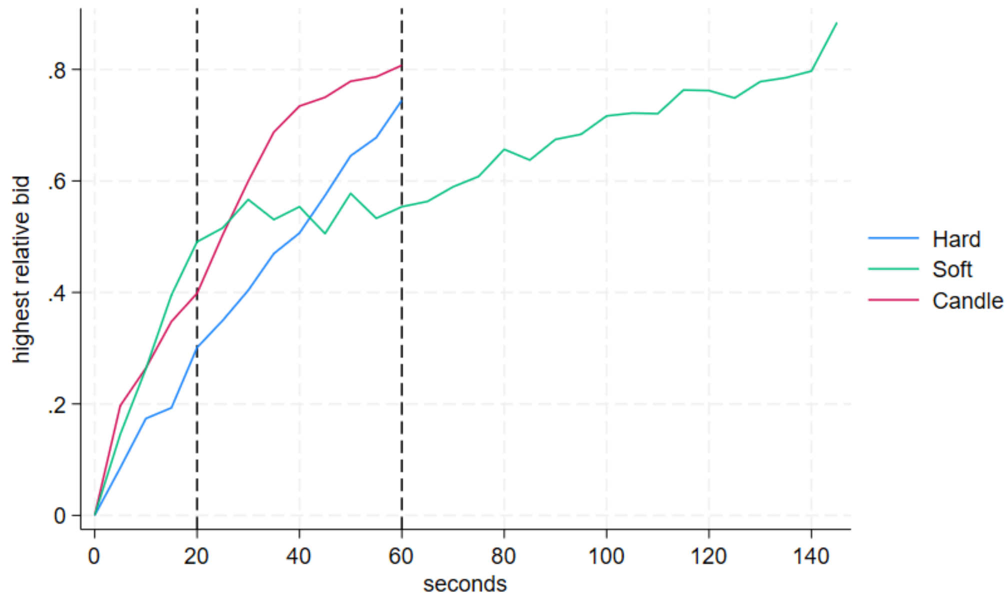

Figure 11: Average currently highest relative bid combinations over time
Note: The currently highest relative bid combination is the sum of bids on the package that would win the auction if it ended in this moment, divided by the value of the second-most-valuable allocation

combination over time in all three treatments (similar to Figure 6 for the field data). As conjectured in Hypothesis 3, bids in Candle increase faster than in Hard but they certainly do not increase instantaneously after the start of the ending phase. Bids in Soft need almost twice as much time to reach the revenues of the other two treatments.

Result 3 (Delayed Bidding in Candle Auction)**.** *The low-revenue outcomes in the candle auction are a result of the auction ending too early. Bidders escalate their bids earlier in the candle auction than under the hard-close rule, but not sufficiently to offset early ending times.*

5.3.4 Combinatorial Aspects

The main challenge in our combinatorial experimental design for the two flexible bidders is to agree on (1) which package they should target and (2) who should increase their bid in case their joint bids are below those of the inflexible bidder. The first challenge is a coordination problem; the second has a more battle-of-the-sexes flavor. We expect the coordination problem to be particularly severe when the incentives of the inflexible bidders are misaligned, that is, when they have a higher value for the same package.

Overall, bidders solve the combinatorial coordination problems rather well, as indicated by the high efficiency values (see Table 4). However, there are differences. Inflexible bidders win in about 50.5% of cases, although they should have won in only about 43.4% of auctions given the randomly drawn valuations in the experiments (there are no significant differences across treatments).[27]

Table 6 shows in more detail which factors matter for efficiency. In the OLS regressions with standard errors clustered on the group level, relative efficiency (in %) is regressed on treatment dummies, the dummy for a (globally) collusive group (coll_global), the dummy for local chat between flexible bidders (coll_local), and interaction terms between a dummy that is 1 if the inflexible bidder should win (under efficiency) and a dummy that is 1 if the incentives of flexible bidders are misaligned (i.e. they both prefer the same package).

The first specification in Table 6 reiterates our earlier finding that relative efficiency is, on average, not different between treatments. The second specification points to a potential role of global and local collusion. The third specification shows that (i) global agreement on collusion hurts efficiency, (ii) local chat between flexible bidders helps efficiency, and (iii) the interaction term shows that when the inflexible bidder should win, then misalignment increases efficiency, but vice versa when the inflexible bidder should not win. We find (ii) and (iii) especially noteworthy:

Result 4 (Combinatorial Aspects)**.** *Communication between the flexible bidders helps efficiency. When the inflexible bidder should win, misalignment of the flexible bidders' incentives increases efficiency; however, the opposite is true when the inflexible bidder should not win.*

[27]Excluded are auctions in which the valuations are equal, so that it does not matter who wins

	relative efficiency		
	(1)	(2)	(3)
(constant)	0.934***	0.926***	0.901***
	(0.011)	(0.012)	(0.020)
Soft	-0.001		0.016
	(0.021)		(0.018)
Hard	-0.006		-0.008
	(0.015)		(0.015)
coll_global=1		-0.046*	-0.054**
		(0.025)	(0.027)
coll_local=1		0.023*	0.027**
		(0.012)	(0.012)
inflexible_should_win1 × misaligned=1			0.037***
			(0.014)
inflexible_should_win1 × misaligned=0			0.035
			(0.022)
inflexible_should_win0 × misaligned=1			0.025
			(0.017)
Num.Obs.	540	540	523
R^2	0.001	0.034	0.061

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 6: Determinants of relative efficiency. OLS results.
Note: The sample size in specification (3) is reduced because we excluded auctions in which the valuations are equal, so that it does not matter who wins. Standard errors in parentheses are clustered on the group level. Soft and Hard are treatment dummies; coll_global (local) are dummies which are 1 if the auction was coded as globally (locally) collusive. Inflexible_should_win is a dummy and is 1 if it is efficient if the inflexible bidder wins; misaligned is a dummy and is 1 if the flexible bidders have the higher value for the same package.

5.3.5 Discussion

In summary, our findings support Hypotheses 3 and 4. Bidders in the candle treatment escalate their bids earlier than those under the hard-close rule. Also, revenue and efficiency levels are no worse in the candle auction.

However, the mechanisms driving the latter findings have proved subtle and only partially align with our initial conjectures. Revenues are comparable not solely because early bid escalation offsets the random ending time, but also because the candle auction appears more resilient to bidder collusion. Similarly, the observed efficiency is less a direct result of the candle format itself and more a consequence of improved coordination facilitated by bidder communication.

6 Conclusion

We considered a dynamic combinatorial first-price auction with a random-close rule known as the candle auction. In a candle auction, bidders should escalate their bids early, producing outcomes similar to more traditional mechanisms. Field data confirm that the highest bidder at the end is often the winner at the random closing time. Our experiment further supports our theoretical predictions.

Crucially, the candle auction goes beyond merely matching conventional formats in efficiency and revenue; it is more robust to collusion. Collusion resistance is a valuable characteristic for digital marketplaces, where preventing communication and coordination among bidders is challenging. Moreover, and in line with Füllbrunn and Sadrieh (2012), the candle mechanism mitigates prominent online-auction issues such as delayed bidding and sniping (Roth and Ockenfels, 2002). We studied a first-price candle auction as this was the type used in our field data from blockchain auctions. Arguably, the second price format studied by Füllbrunn and Sadrieh (2012) may have even better efficiency properties, though.

The candle auction also has some crucial theoretical merits. As we have shown, it admits a belief-free equilibrium in simple, incremental strategies even though its rules are non-standard. And second, we know that the candle auction mitigates issues arising from network latencies in online auctions, such as front-running (Häfner and Stewart, 2024). Together with recent technological advances — especially verifiable randomness (Micali et al., 1999), which enables an auctioneer to credibly commit to a random ending time — the candle auction thus stands as a promising closing rule for dynamic online auctions.

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Online Appendix: Additional Materials

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A Proofs

Proof of Proposition 1. Under the proposed strategies, bidding stops at $v_{(2)}$ (if $v_{(1)} \geq v_{(2)} + \Delta$) or $v_{(2)} - \Delta$ (if $v_{(1)} = v_{(2)}$). Because values are bounded above by one, bidding stops at time $\bar{\tau}_m := \frac{1}{m\Delta}$ the latest, which is strictly below 1 by assumption. As we hold $\Delta > 0$ fixed, $\lim_{m\to\infty} \bar{\tau}_m = 0$; i.e., the resulting payment is equal to $\min\{v_{(2)}, v_{(1)} - \Delta\}$ with probability one. Similarly, the auction winner is one of the bidders who submitted in the last round in which a bid was submitted. By construction of the bidding functions, the bid space B, and the valuation space V, this is one of the bidders with the highest value. Together, we have claim (ii).

We show claim (i) by establishing the following: For any $\epsilon > 0$, there is $M > 0$ such that for all $m > M$, the *ex-post* continuation gain from switching to any alternative strategy is bounded by ϵ for any $t \in [0, 1)$ and history h_t. As required by equilibrium, we take a bidder i with value v_i and suppose the other bidders follow the conjectured equilibrium strategies. Then, we show that, in the case bidder i knows the opponent profile of valuations $v_{-i} = (v_1, ..., v_{i-1}, v_{i+1}, ..., v_n)$ and can thus anticipate their course of play perfectly, there is no valuation profile such that, going forward, bidder i can gain more than ϵ by changing strategies.[1]

To this end, fix a state s, time $t \in [0, 1)$, and a bidder i with value v_i. First, when $b^{max} \geq v_i - \Delta$, then it is best for bidder i not to submit a bid at all future opportunities. But doing so corresponds to the conjectured equilibrium strategy. Next consider the case $b^{max} < v_i - \Delta$. We distinguish two cases: (i) $b^{max} \geq v_{(2)}$ and (ii) $b^{max} < v_{(2)}$.

- Case (i): $b^{max} \geq v_{(2)}$. Then, $v_i > v_{(2)}$, i.e., our bidder holds the highest value among all bidders. Also, no other bidder will bid in the future. So, if the current highest bid was submitted by bidder i, then bidder i fares best by sticking to her equilibrium

[1]For $t = 1$, nothing needs to be shown because the auction ending in $t = 1$ is a zero-probability event and, accordingly, the continuation utility (unconditional on the ending time) is zero, no matter what bid the bidder submits in $t = 1$.

strategy, which is not to submit a further bid. If the current highest bid is by some other bidder, then bidder i also fares best by following her equilibrium strategy: to increase the current winning bid by Δ and then not bid any further. Last, if bidder i holds the highest bid with $\hat{n} \geq 1$ other bidders, then increasing the bid once is also optimal: $1/(1+\hat{n})(v_i - b^{\max}) \leq v_i - b^{\max} - \Delta$ because $v_i - b^{\max} \geq 2\Delta$.

- Case (ii): $b^{max} < v_{(2)}$. Now, three subcases must be distinguished:

  1. $v_i \leq v_{(3)}$: In that case, the highest bid will increase and reach $\min\{v_{(1)} - \Delta, v_{(3)}\}$ in at most $v_{(3)}/\Delta$ units of time (if $t = 1$ is not reached before), irrespective of bidder i's strategy. Once the highest bid reaches such a value, the optimal strategy for bidder i is not to bid anymore, i.e., to follow the conjectured equilibrium strategy. Before the highest bid reaches such a value, though, our bidder might attempt to overbid the others, but the maximum gain from doing so is bounded above by the maximum time it takes to reach $v_{(3)}$ times the winning probability per opportunity, which is $v_{(3)}/(m\Delta)$.

  2. $v_i = v_{(2)}$: In this case, the highest bid will increase and reach $\min\{v_{(1)} - \Delta, v_{(3)}\}$ in at most $v_{(3)}/\Delta$ units of time (if $t = 1$ is not reached before), irrespective of the bidder i's strategy. By the same argument above, the gain from overbidding the others before the highest bid reaches such a value is thus bounded above by $v_{(3)}/(m\Delta)$. Once the highest bid surpasses $v_{(3)}$ but before it reaches $v_{(2)}$, any delay in bidding comes at the cost of the other bidder having the highest bid in the next round. The gain of delaying is thus bounded by the gain of overbidding the other bidder until the highest bid reaches $v_{(2)}$, which is $(v_{(2)} - v_{(3)})/(m\Delta)$ in expectation. Further, any attempt to raise the highest bid by more than Δ will induce the other bidder to catch up in the following round. So, the maximum gain from deviating while the highest bid is between $v_{(2)}$ and $v_{(3)}$ is bounded above by $(v_{(2)} - v_{(3)})/(m\Delta)$. Once the highest bid reaches $v_{(2)}$, the optimal strategy

for bidder i is not to bid anymore, i.e., to follow the conjectured equilibrium strategy. Consequently, the maximum gain from deviating is bounded above by the maximum time it takes to reach $v_{(2)}$ times the winning probability per opportunity, which is $v_{(2)}/(m\Delta)$.

3. $v_i = v_{(1)}$: If bidder i has the highest value, then by the arguments above, the maximum gain from deviating is bounded above by the number of increments it takes for the highest bid to reach $v_{(2)} + \Delta$ (if $t = 1$ is not reached before), which is $(v_{(2)} + \Delta)/\Delta$, multiplied by the winning probability per opportunity, $1/m$.

In all cases, the bound on the possible gains from deviating vanishes in m, and it does so uniformly in $t \in [0, 1)$ and v. Consequently, following the conjectured equilibrium strategies indeed constitutes state-wise ex-post ϵ-equilibrium. □

Proof of Proposition 2. When values are strongly complementary according to Definition 4, then everyone with a value $v_{iY} > \Delta$ bids at least once on the grand package, Y, when following their incremental strategy from Definition 3. Indeed, conditions (ii) and (iii) fail at the beginning of the auction. And because $v_{iY} > \max_{y \in \mathcal{A}_{-Y}} \sum_j v_{jy_j}$ holds for all bidders' realized values, condition (i) in (3) never holds for $x = Y$.

An additional consequence of $v_{iY} > \max_{y \in \mathcal{A}_{-Y}} \sum_j v_{jy_j}$ holding for all bidders' realized values, is that bidding will continue exactly until the highest bid on Y, $b_Y^{\max}$, is within Δ of $v_{(2)Y}$, where the winning allocation corresponds to Y and the bidder with the highest value for Y holds the winning bid. Since bidding escalates immediately in the limit $m \to \infty$, we obtain the claim in Proposition 2.ii.

As regards claim (i), we first observe that under the conjectured equilibrium profile, the ex-post utilities in $t = 0$ satisfy $\lim_{m\to\infty} U_{i0}(\beta^*, v; h_0) = v_{(1)Y} - v_{(2)Y}$ if $v_i = v_{(1)Y}$ and zero otherwise. In the limit, bidder i only obtains positive utility when holding the highest value among all bidders for the grand package Y, and $v_{(1)Y} > v_{(2)Y}$.

Now, for finite but large m, let $\hat{T}_m$ be the round in which the bid on the grand package reaches $v_{(2)Y}$ (or $v_{(2)Y} - \Delta$ if two bidders hold the same highest value) under the conjectured equilibrium profile β^*. Because valuations are bounded above by one, it holds that $\hat{T}_m \leq \frac{1}{m\Delta}$, where $\frac{1}{m\Delta} < 1$ because m is large.

Since we assume strong complementarity on the top, deviations that change bidding on smaller packages $x \subset Y$ can be profitable at most in periods $t \leq \hat{T}_m$. The reason is that any profitable deviation must involve bidding below value, but at least one opponent will keep raising the bid on the grand package. Consequently, at $\hat{T}_m$, the highest bid required to win any of these smaller packages will have reached or exceeded the respective values for all bidders. Since $\lim_{m\to\infty} \bar{T}_m = 0$, any positive deviation utilities associated with these deviations vanish, independent of v_i.

So, we only need to consider bid deviations on the grand package. Then, three cases are relevant: (i) $v_{iY} \leq v_{(3)Y}$, (ii) $v_{iY} = v_{(2)Y}$, and (iii) $v_{iY} = v_{(1)Y}$. To establish the claim in Proposition 2.i, we can reuse the arguments in the proof of Proposition 1, under the three subcases 1-3 in case (ii), replacing $v_{(k)}$ with $v_{(k)Y}$, $k = 1, 2, 3$, and v_i with v_{iY}. $\square$

B Experiment: Additional Figures

In this section, we present additional figures on the experiment, as referenced in the text. The original figures are in German; we present the English translations. The full instructions and the comprehension quiz, including their translations to English, are in the Online Appendix.

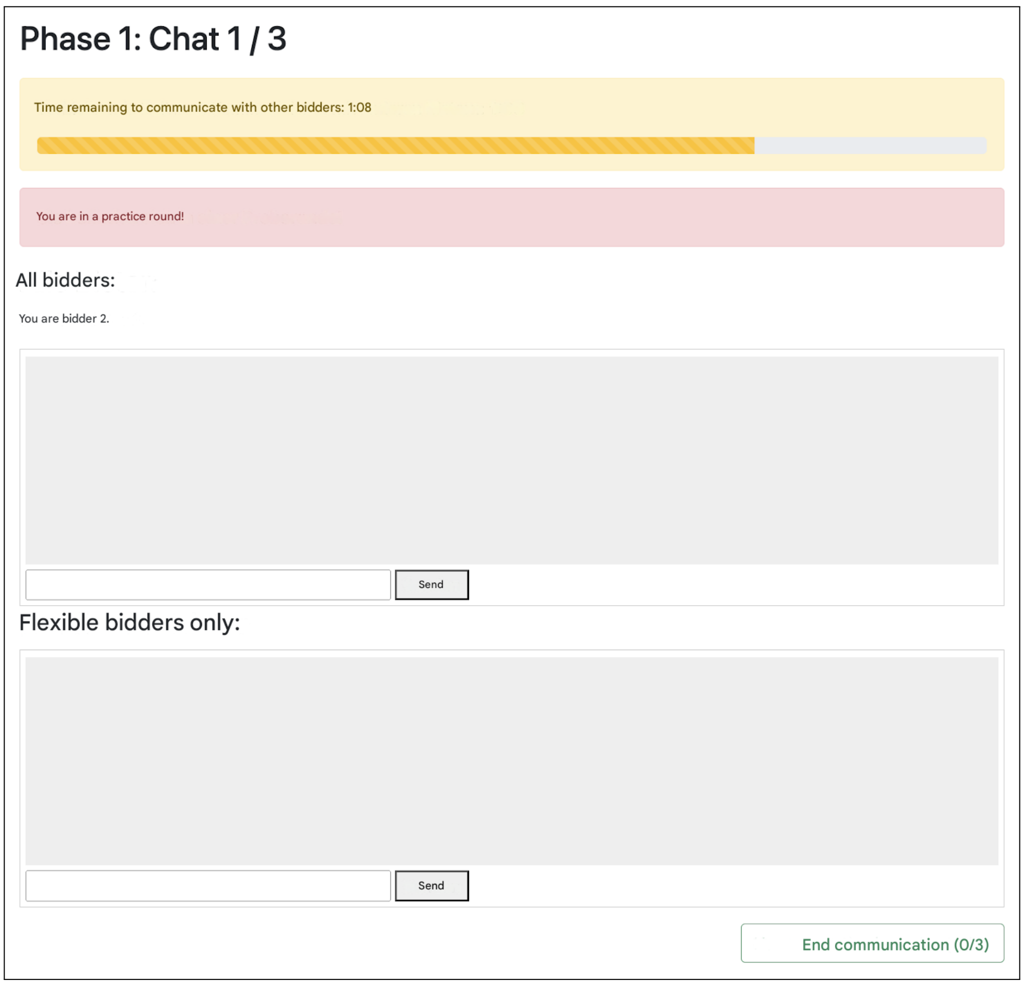


Figure 12: User interface: communication stage for flexible bidder (English translation). Inflexible bidders did only see the first chat box.

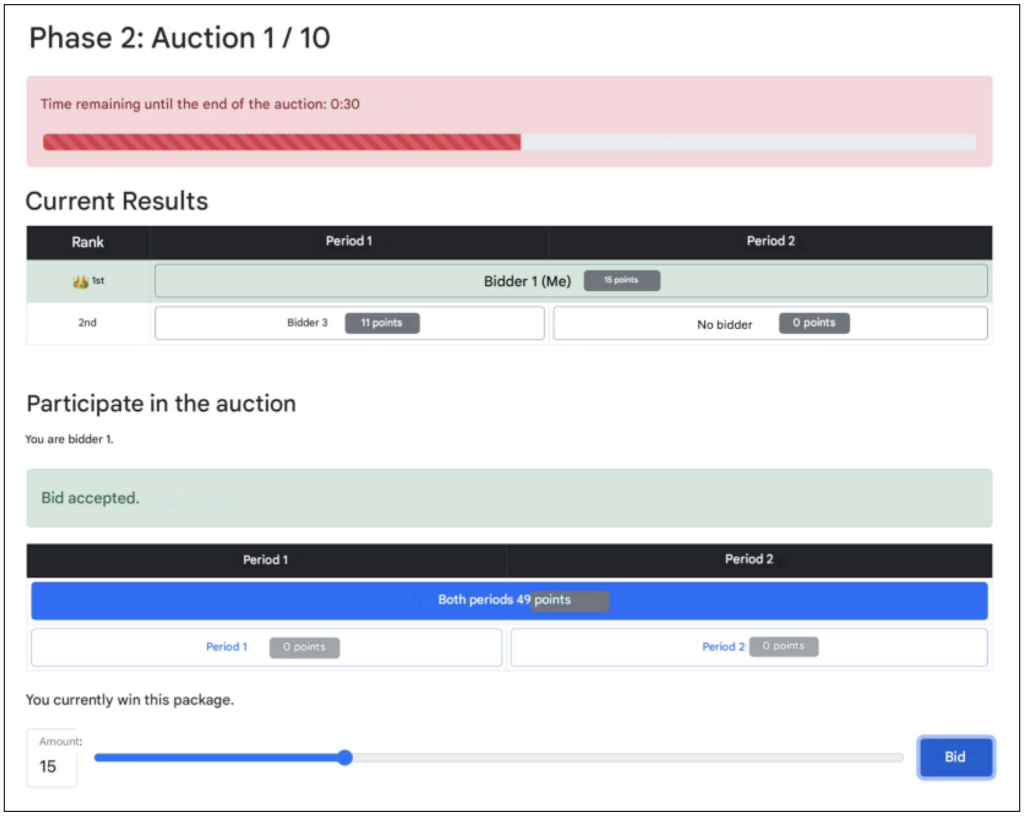


Figure 13: User interface: bidding stage (English translation).

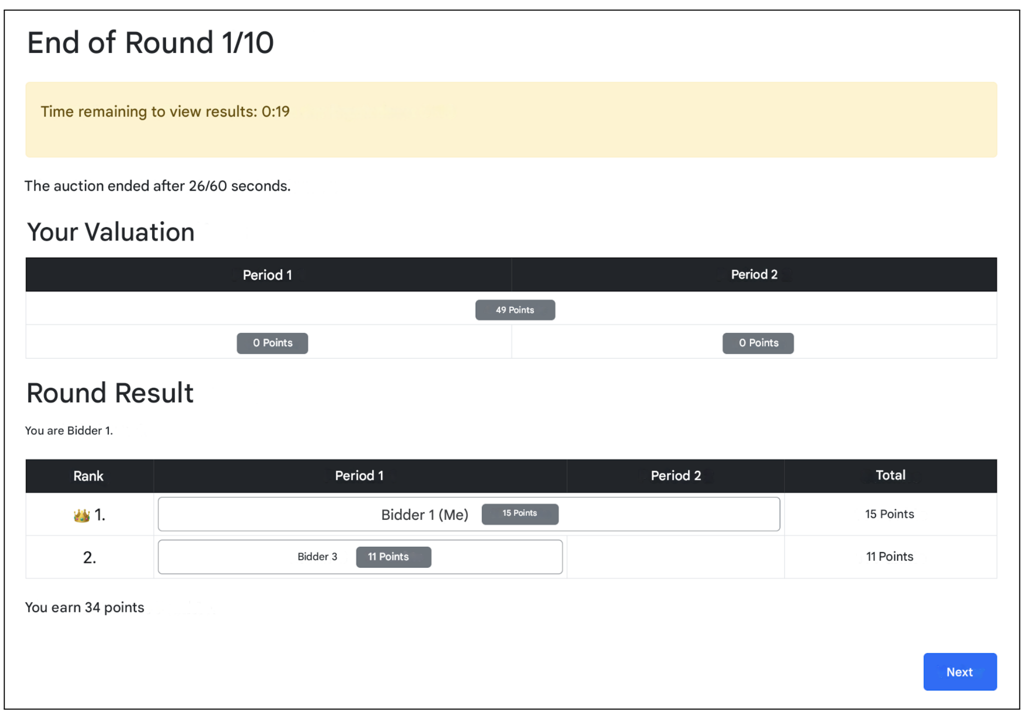


Figure 14: User interface: outcome stage (English translation). The snapshot is taken from a candle auction, where subjects also received feedback about the retroactive ending time.

C Experiment: Instructions (German Original)

This section contains the (German) instructions that we showed the subjects before the experiment. English translations are in Section E below. For each of the treatments, the instructions differed in one paragraph, describing the respective auction. The treatments are indicated in the top-right corner of the respective instructions. HC stands for hard-close rule; AC stands for the soft-close rule (A stands for activity); CA stands for candle auction. There was a single version of comprehension quiz for all treatments to check the participant's understanding of the experiment.

Anleitung

Ablauf des Experiments:

1. Lesen der Anleitungen
2. Kontrollfragen zum Verständnis
3. Übungs-Auktionen: 3 Runden
4. Auktionen: 10 Runden
5. Fragebogen
6. Bezahlung

Sie nehmen heute an einem Entscheidungs-Experiment teil. Wenn Sie die nachfolgenden Erklärungen genau lesen, können Sie Geld verdienen. Der Betrag, den Sie erhalten, hängt von Ihren Entscheidungen und den Entscheidungen der anderen Teilnehmer ab.

Für die gesamte Dauer des Experiments ist es nicht erlaubt, mit anderen Teilnehmern zu sprechen. Eine Verletzung dieser Regel führt zum Ausschluss vom Experiment und der Bezahlung.

Wenn Sie etwas nicht verstehen sollten, schauen Sie bitte noch einmal in diese Anleitung oder geben Sie uns ein Handzeichen. Wir werden dann zu Ihnen kommen und Ihre Frage persönlich beantworten.
Während des Experiments sprechen wir nicht von Euros, sondern von abstrakten **Punkten**. Die von Ihnen während des Experiments erzielten Punkte werden wie folgt in Euro umgerechnet:

1 Punkt = 2 €

Am Ende bekommen Sie die für die Auszahlung relevanten Punkte umgerechnet in Euro und zusätzlich 15 **€** für Ihr Erscheinen in **bar** ausbezahlt.
Auf den folgenden Seiten erläutern wir Ihnen den genauen Ablauf des Experiments. Nachdem Sie die Anleitung gelesen und verstanden haben, beantworten Sie die Kontrollfragen am Ende der Anleitung, die Ihnen helfen sollen, den Ablauf besser zu verstehen. Das Experiment beginnt erst dann, wenn alle Teilnehmer mit dem Ablauf des Experiments vollständig vertraut sind und die Kontrollfragen richtig beantwortet haben. Die Anleitungen sind für alle Teilnehmer dieselben.

Das Experiment: Überblick

Sie werden in diesem Experiment als **Bieter** an **Auktionen** um das Nutzungsrecht an einem fiktiven Gut teilnehmen, das in zwei Perioden unterteilt ist. Wenn Sie ein Nutzungsrecht ersteigern, erhalten Sie Punkte. Dabei ist es möglich, das Nutzungsrecht für beide Perioden (Periode 1 *und* Periode 2) oder für eine der beiden Perioden zu ersteigern.

Sie werden für die Auktionen zufällig in Gruppen aus **drei** Teilnehmern aus diesem Raum aufgeteilt. Jede Auktion hat also **drei** Bieter. Insgesamt spielen Sie zehn gewertete Auktionen (=Runden). Weder Sie noch die anderen Teilnehmer erfahren etwas über die Identität der anderen Teilnehmer in den Gruppen – weder vor noch nach dem Experiment.

Vor den zehn gewerteten Auktionen nehmen Sie an drei Übungs-Auktionen teil. Hier können Sie sich mit der Benutzeroberfläche vertraut machen. Nach den Übungs-Auktionen werden die Gruppen einmalig neu zusammengestellt und bleiben dann für alle 10 gewerteten Auktionen gleich.

Das fiktive Gut:

In jeder Auktion bieten die Teilnehmer auf Nutzungsrechte an einem fiktiven Gut. Es gibt **drei** verschiedene Pakete, welche das Nutzungsrecht am fiktiven Gut beschreiben. Das Paket „Beide Perioden“ (im folgenden Screenshot mit 40 Punkten bewertet) erlaubt die Nutzung des Gutes für zwei Perioden. Paket „Periode 1“ (19 Punkte) erlaubt die Nutzung in Periode 1, Paket „Periode 2“ (21 Punkte) in Periode 2. Die Wertschätzungen für die Pakete werden zu Beginn jeder Runde vom Computer zufällig für alle Bieter neu ausgelost (siehe weiter unten für Details). Sie können nur Ihre eigene Wertschätzung sehen. Die Wertschätzungen der anderen Bieter können davon abweichen.

<u>Die Rollen:</u>

In diesem Experiment sind alle Bieter in zwei unterschiedliche Rollen eingeteilt. In jeder Auktion gibt es *zwei* **flexible Bieter** und *einen* **unflexiblen Bieter**.

- **Flexible Bieter** können auf alle drei Pakete bieten.
- **Unflexible Bieter** können nur auf Paket „Beide Perioden" bieten.

Ihre Rolle wird Ihnen am Anfang des Experiments auf dem Bildschirm mitgeteilt. Die Rollenverteilung bleibt über das gesamte Experiment gleich.

Die Wertschätzungen werden nach dem folgenden Verfahren zufällig vom Computer bestimmt. Sie sind unabhängig von den Vorrunden und von allen anderen Bietern.

Wertschätzung des flexiblen Bieters: Die Wertschätzung für Paket „Beide Perioden" ist immer 40. Zusätzlich wird eine zufällige Zahl X zwischen 0 und 40 bestimmt, um die Wertschätzung für Paket Periode 1 zu bestimmen**.** Dabei sind alle ganzen Zahlen zwischen 0 und 40 gleich wahrscheinlich. Die Wertschätzung für Paket Periode 2 ergibt sich dann als 40 - X. Ist X zum Beispiel 10, dann hat dieser Bieter eine Wertschätzung von 10 für Paket Periode 1 und von 30 (= 40-10) für Paket Periode 2.

Wertschätzung des unflexiblen Bieters: Es wird eine zufällige Zahl zwischen 45 und 55 gezogen, diese ist die Wertschätzung für Paket „Beide Perioden“**.** Alle ganzen Zahlen zwischen 45 und 55 sind gleich wahrscheinlich. Die Wertschätzungen für die beiden anderen Pakete sind 0.

Wenn Sie ein Paket in der Auktion gewinnen, dann ergibt sich **Ihre Auszahlung** für diese Runde aus der **Differenz Ihrer Wertschätzung und Ihrem Gebot**.

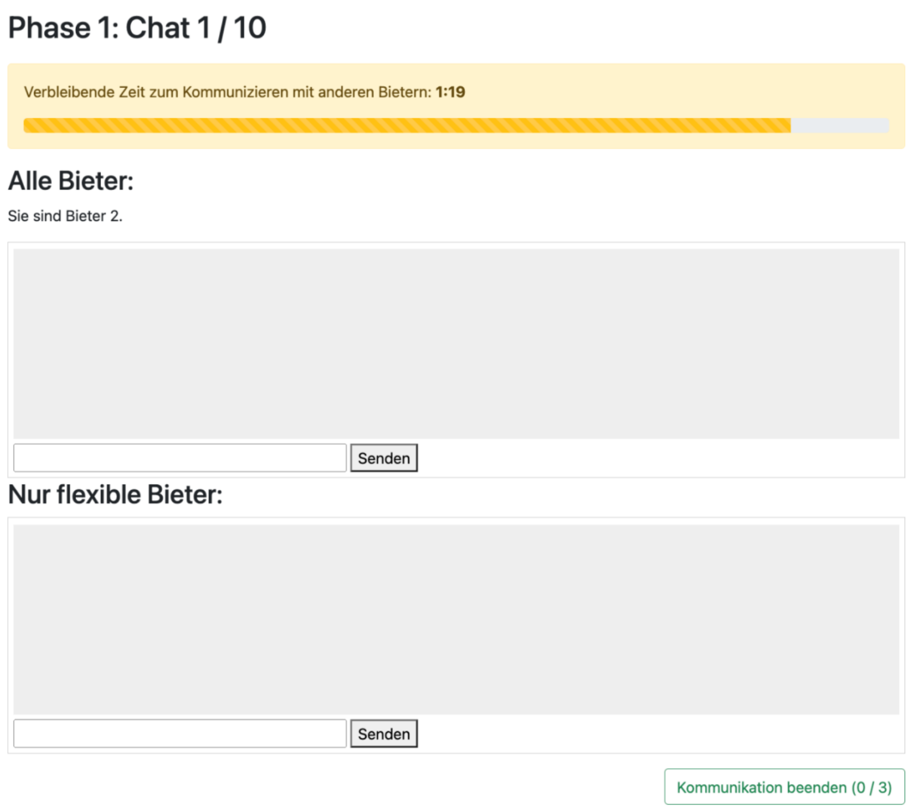
Im Beispiel oben: Ihre Wertschätzung für Paket „Beide Perioden“ ist 40. Angenommen Sie haben 30 geboten und die Auktion gewonnen. Dann wäre Ihr Gewinn 10.

Als flexibler Bieter können Sie auch zwei Pakete gewinnen. In diesem Fall werden die Auszahlungen von beiden Paketen addiert. Gewinnen Sie die Auktion nicht, dann ist Ihre Auszahlung für diese Runde gleich 0.

Kommunikation

Vor jeder Auktion haben Sie die Möglichkeit, mit den anderen Bietern aus Ihrer Gruppe zu chatten. Dabei sehen Sie folgende Benutzeroberfläche:

AC



Abhängig von Ihrer Rolle, sehen Sie entweder ein oder zwei Chatfenster. Ein flexibler Bieter hat die Möglichkeit, sowohl mit dem anderen flexiblen Bieter zu chatten als auch im allgemeinen Chat teilzunehmen. Der unflexible Bieter kann nur im Chat mit allen Teilnehmern chatten.

Hinweis: Im Chat gibt es gewisse Regeln. Es ist nicht erlaubt, sich selbst oder eine andere Person zu identifizieren. Außerdem sind beleidigende und unangebrachte Kommentare zu unterlassen. Ein Zuwiderhandeln führt zum Ausschluss vom Experiment und der Bezahlung.

Ablauf der Auktion

Direkt nach der Kommunikationsphase beginnt die Auktion, in der alle Bieter versuchen, ein oder mehrere Pakete zu gewinnen, indem sie passende Gebote abgeben. Ihr Gebot kann nicht höher sein als Ihre Wertschätzung für ein Paket.

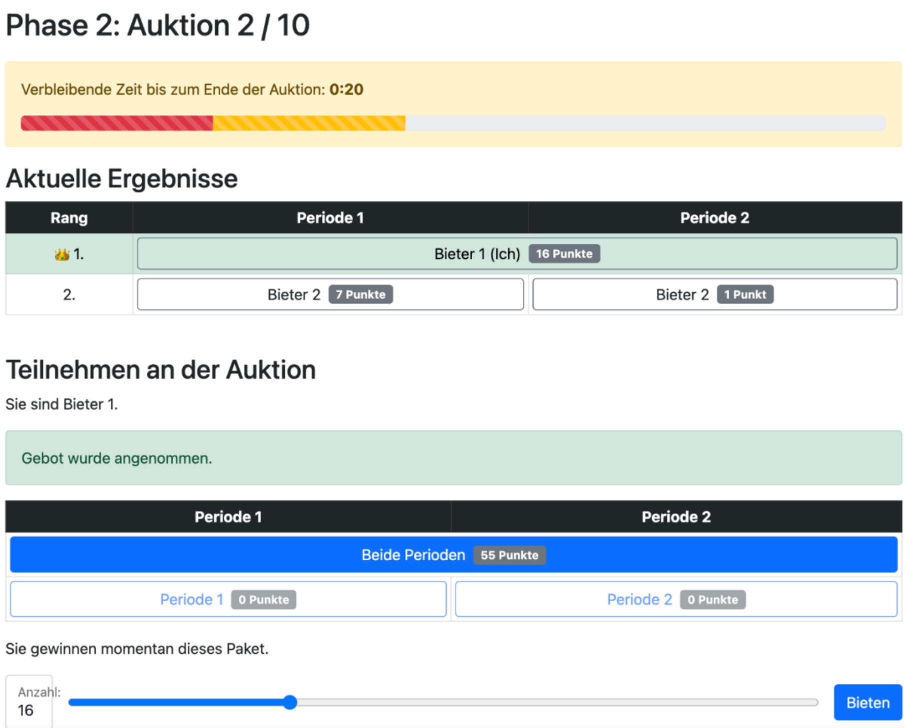
Eine Auktion dauert mindestens **45 Sekunden**. Jedoch setzt jedes neue Gebot in den letzten 10 Sekunden der Auktion den Timer (dargestellt als gelber bzw. roter Balken) **wieder auf 10 Sekunden zurück**. Das heißt, die Auktion endet erst, wenn in den letzten 10 Sekunden kein neues Gebot abgegeben wird.

Jeder Bieter kann auf mehrere Pakete gleichzeitig bieten und immer neue Gebote abgeben, wenn das neue Gebot höher als das bestehende ist.

Gewinnberechnung: **Gewonnen hat das Gebot oder diejenigen Gebote, welche den Wert des gesamten Nutzungsrechts maximieren.** Das bedeutet, dass die Nutzungsdauer nur aufgeteilt wird, wenn die Summe der zwei Gebote auf Pakete Periode 1 und 2 höher ist als das Gebot auf Paket „Beide Perioden“.

Beispiel: Angenommen, das Höchstgebot auf Paket „Beide Perioden“ ist 40, das auf Paket Periode 1 ist 20 und das auf Paket Periode 2 ist 25. Dann bekommen die Bieter für Pakete Periode 1 und 2 den Zuschlag, da die Summe der Gebote mit 45 = 20 + 25 höher ist als das Gebot auf Paket „Beide Perioden“ mit 40.

Sie werden die folgende Benutzeroberfläche im Experiment sehen.



Erklärung der Benutzeroberfläche

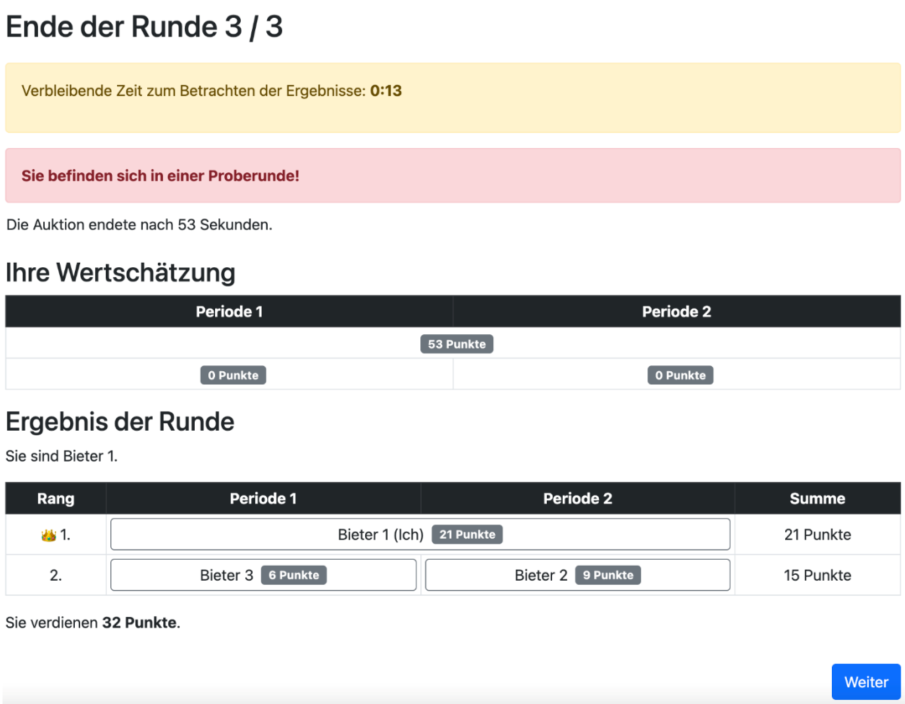
“Aktuelle Ergebnisse:” Hier sehen Sie das derzeitige Ergebnis der Auktion. In der ersten Zeile sehen Sie das aktuelle Gebot für Paket „Beide Perioden“, in der zweiten Zeile die jeweiligen Gebote für Perioden 1 und 2. In der Spalte “Rang” zeigt eine Krone an, welches Paket oder welche Pakete in der Auktion vorne liegen.

“Teilnehmen an der Auktion”: Hier können Sie Ihr Gebot eingeben. Klicken Sie dazu auf eines der verfügbaren Felder und nutzen Sie anschließend den Slider (oder die direkte Eingabe) und klicken Sie auf “Bieten”. Sie können den Slider nutzen, um das Gebot einzustellen oder das Gebot direkt eingeben, indem Sie auf die linke Box klicken.

Hinweis: Sobald Sie ein Paket ausgewählt haben, erscheint ein kleiner Hinweistext, der Ihnen vorschlägt, wie viel Sie bieten müssten, damit dieses Paket (eventuell zusammen mit einem anderen Gebot) vorne liegen würde.

Feedback Bildschirm:

Nach jeder Auktion bekommen Sie Feedback, wann die Auktion beendet wurde, wer die Gewinner waren und wie viel Sie verdient haben.



Bezahlung:

Am Ende des Experiments wird zufällig eine Runde ausgewählt. Nur die Auszahlungen von dieser Runde werden in Euro umgerechnet und am Ende des Experiments in bar ausbezahlt.

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Vor den zehn gewerteten Auktionen nehmen Sie an drei Übungs-Auktionen teil. Hier können Sie sich mit der Benutzeroberfläche vertraut machen. Nach den Übungs-Auktionen werden die Gruppen einmalig neu zusammengestellt und bleiben dann für alle 10 gewerteten Auktionen gleich.

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Die Wertschätzungen werden nach dem folgenden Verfahren zufällig vom Computer bestimmt. Sie sind unabhängig von den Vorrunden und von allen anderen Bietern.

Wertschätzung des flexiblen Bieters: Die Wertschätzung für Paket „Beide Perioden“ ist immer 40. Zusätzlich wird eine zufällige Zahl X zwischen 0 und 40 bestimmt, um die Wertschätzung für Paket Periode 1 zu bestimmen**.** Dabei sind alle ganzen Zahlen zwischen 0 und 40 gleich wahrscheinlich. Die Wertschätzung für Paket Periode 2 ergibt sich dann als 40 - X. Ist X zum Beispiel 10, dann hat dieser Bieter eine Wertschätzung von 10 für Paket Periode 1 und von 30 (= 40-10) für Paket Periode 2.

Wertschätzung des unflexiblen Bieters: Es wird eine zufällige Zahl zwischen 45 und 55 gezogen, diese ist die Wertschätzung für Paket „Beide Perioden“**.** Alle ganzen Zahlen zwischen 45 und 55 sind gleich wahrscheinlich. Die Wertschätzungen für die beiden anderen Pakete sind 0.

Wenn Sie ein Paket in der Auktion gewinnen, dann ergibt sich **Ihre Auszahlung** für diese Runde aus der **Differenz Ihrer Wertschätzung und Ihrem Gebot**.

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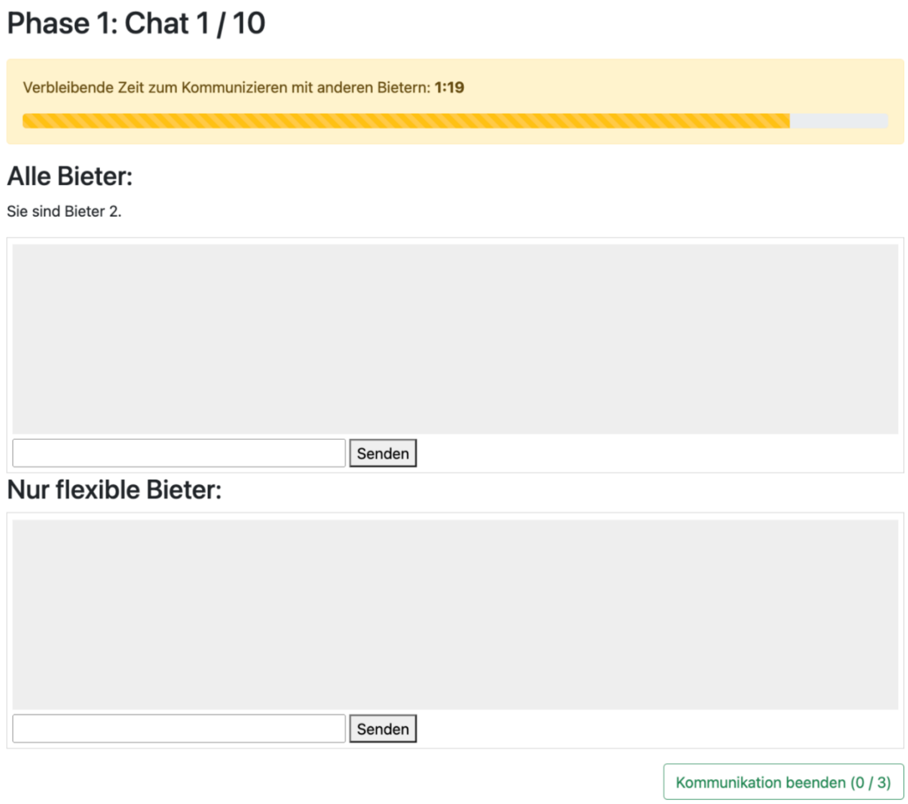
Als flexibler Bieter können Sie auch zwei Pakete gewinnen. In diesem Fall werden die Auszahlungen von beiden Paketen addiert. Gewinnen Sie die Auktion nicht, dann ist Ihre Auszahlung für diese Runde gleich 0.

Kommunikation

Vor jeder Auktion haben Sie die Möglichkeit, mit den anderen Bietern aus Ihrer Gruppe zu chatten. Dabei sehen Sie folgende Benutzeroberfläche:

HC



Abhängig von Ihrer Rolle, sehen Sie entweder ein oder zwei Chatfenster. Ein flexibler Bieter hat die Möglichkeit, sowohl mit dem anderen flexiblen Bieter zu chatten als auch im allgemeinen Chat teilzunehmen. Der unflexible Bieter kann nur im Chat mit allen Teilnehmern chatten.

Hinweis: Im Chat gibt es gewisse Regeln. Es ist nicht erlaubt, sich selbst oder eine andere Person zu identifizieren. Außerdem sind beleidigende und unangebrachte Kommentare zu unterlassen. Ein Zuwiderhandeln führt zum Ausschluss vom Experiment und der Bezahlung.

5

Ablauf der Auktion

Direkt nach der Kommunikationsphase beginnt die Auktion, in der alle Bieter versuchen, ein oder mehrere Pakete zu gewinnen, indem sie passende Gebote abgeben. Ihr Gebot kann nicht höher sein als Ihre Wertschätzung für ein Paket.

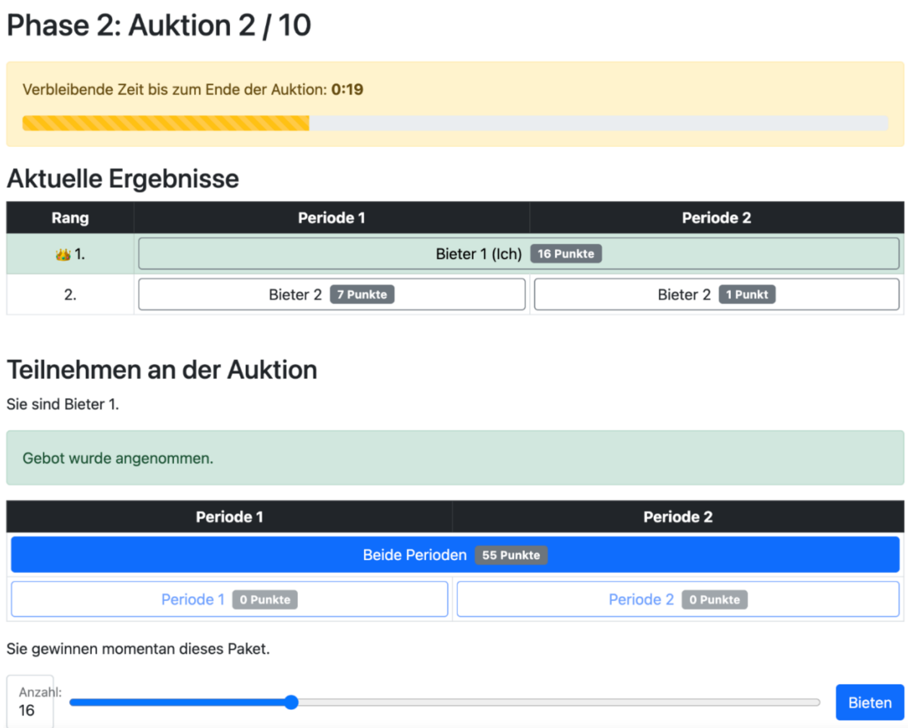
Eine Auktion dauert 60 **Sekunden** (der Timer ist dargestellt als gelber Balken)**.** Gebote, die später abgegeben werden, können nicht mehr berücksichtigt werden.

Jeder Bieter kann auf mehrere Pakete gleichzeitig bieten und immer neue Gebote abgeben, wenn das neue Gebot höher als das bestehende ist.

Gewinnberechnung: **Gewonnen hat das Gebot oder diejenigen Gebote, welche den Wert des gesamten Nutzungsrechts maximieren.** Das bedeutet, dass die Nutzungsdauer nur aufgeteilt wird, wenn die Summe der zwei Gebote auf Pakete Periode 1 und 2 höher ist als das Gebot auf Paket „Beide Perioden".

Beispiel: Angenommen, das Höchstgebot auf Paket „Beide Perioden" ist 40, das auf Paket Periode 1 ist 20 und das auf Paket Periode 2 ist 25. Dann bekommen die Bieter für Pakete Periode 1 und 2 den Zuschlag, da die Summe der Gebote mit 45 = 20 + 25 höher ist als das Gebot auf Paket „Beide Perioden" mit 40.

Sie werden die folgende Benutzeroberfläche im Experiment sehen.



Erklärung der Benutzeroberfläche

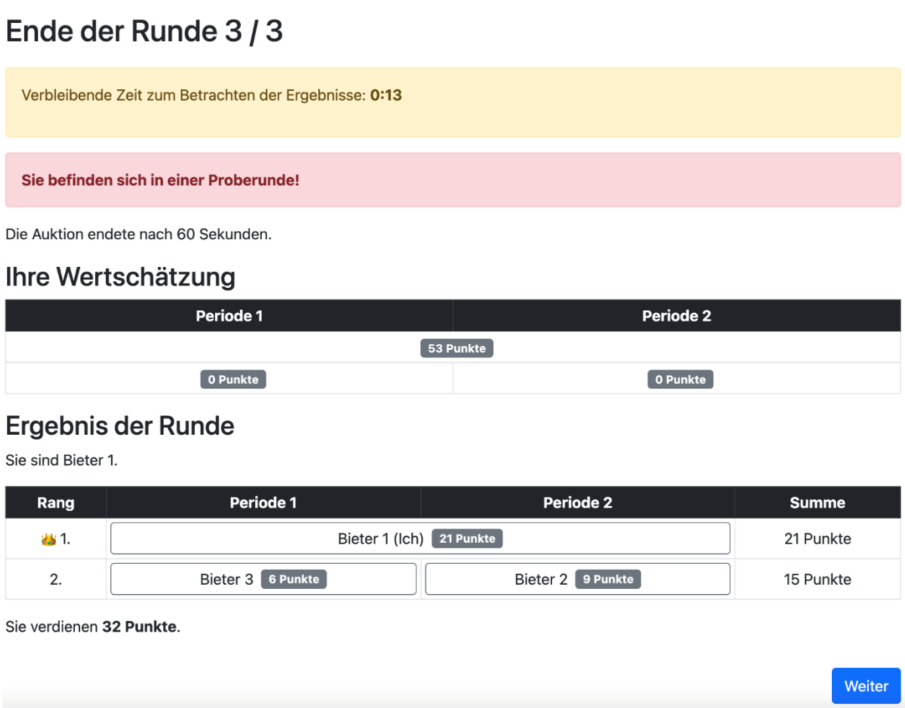
"Aktuelle Ergebnisse:" Hier sehen Sie das derzeitige Ergebnis der Auktion. In der ersten Zeile sehen Sie das aktuelle Gebot für Paket „Beide Perioden", in der zweiten Zeile die jeweiligen Gebote für Perioden 1 und 2. In der Spalte "Rang" zeigt eine Krone an, welches Paket oder welche Pakete in der Auktion vorne liegen.

"Teilnehmen an der Auktion": Hier können Sie Ihr Gebot eingeben. Klicken Sie dazu auf eines der verfügbaren Felder und nutzen Sie anschließend den Slider (oder die direkte Eingabe) und klicken Sie auf "Bieten". Sie können den Slider nutzen, um das Gebot einzustellen oder das Gebot direkt eingeben, indem Sie auf die linke Box klicken.

Hinweis: Sobald Sie ein Paket ausgewählt haben, erscheint ein kleiner Hinweistext, der Ihnen vorschlägt, wie viel Sie bieten müssten, damit dieses Paket (eventuell zusammen mit einem anderen Gebot) vorne liegen würde.

Feedback Bildschirm:

Nach jeder Auktion bekommen Sie Feedback, wann die Auktion beendet wurde, wer die Gewinner waren und wie viel Sie verdient haben.



Bezahlung:

Am Ende des Experiments wird zufällig eine Runde ausgewählt. Nur die Auszahlungen von dieser Runde werden in Euro umgerechnet und am Ende des Experiments in bar ausbezahlt.

Anleitung

Ablauf des Experiments:

1. Lesen der Anleitungen
2. Kontrollfragen zum Verständnis
3. Übungs-Auktionen: 3 Runden
4. Auktionen: 10 Runden
5. Fragebogen
6. Bezahlung

Sie nehmen heute an einem Entscheidungs-Experiment teil. Wenn Sie die nachfolgenden Erklärungen genau lesen, können Sie Geld verdienen. Der Betrag, den Sie erhalten, hängt von Ihren Entscheidungen und den Entscheidungen der anderen Teilnehmer ab.

Für die gesamte Dauer des Experiments ist es nicht erlaubt, mit anderen Teilnehmern zu sprechen. Eine Verletzung dieser Regel führt zum Ausschluss vom Experiment und der Bezahlung.

Wenn Sie etwas nicht verstehen sollten, schauen Sie bitte noch einmal in diese Anleitung oder geben Sie uns ein Handzeichen. Wir werden dann zu Ihnen kommen und Ihre Frage persönlich beantworten.

Während des Experiments sprechen wir nicht von Euros, sondern von abstrakten **Punkten**. Die von Ihnen während des Experiments erzielten Punkte werden wie folgt in Euro umgerechnet:

1 Punkt = 2 €

Am Ende bekommen Sie die für die Auszahlung relevanten Punkte umgerechnet in Euro und zusätzlich 15 **€** für Ihr Erscheinen in **bar** ausbezahlt.

Auf den folgenden Seiten erläutern wir Ihnen den genauen Ablauf des Experiments. Nachdem Sie die Anleitung gelesen und verstanden haben, beantworten Sie die Kontrollfragen am Ende der Anleitung, die Ihnen helfen sollen, den Ablauf besser zu verstehen. Das Experiment beginnt erst dann, wenn alle Teilnehmer mit dem Ablauf des Experiments vollständig vertraut sind und die Kontrollfragen richtig beantwortet haben. Die Anleitungen sind für alle Teilnehmer dieselben.

Das Experiment: Überblick

Sie werden in diesem Experiment als **Bieter** an **Auktionen** um das Nutzungsrecht an einem fiktiven Gut teilnehmen, das in zwei Perioden unterteilt ist. Wenn Sie ein Nutzungsrecht ersteigern, erhalten Sie Punkte. Dabei ist es möglich, das Nutzungsrecht für beide Perioden (Periode 1 *und* Periode 2) oder für eine der beiden Perioden zu ersteigern.

Sie werden für die Auktionen zufällig in Gruppen aus **drei** Teilnehmern aus diesem Raum aufgeteilt. Jede Auktion hat also **drei** Bieter. Insgesamt spielen Sie zehn gewertete Auktionen (=Runden). Weder Sie noch die anderen Teilnehmer erfahren etwas über die Identität der anderen Teilnehmer in den Gruppen – weder vor noch nach dem Experiment.

Vor den zehn gewerteten Auktionen nehmen Sie an drei Übungs-Auktionen teil. Hier können Sie sich mit der Benutzeroberfläche vertraut machen. Nach den Übungs-Auktionen werden die Gruppen einmalig neu zusammengestellt und bleiben dann für alle 10 gewerteten Auktionen gleich.

Das fiktive Gut:

In jeder Auktion bieten die Teilnehmer auf Nutzungsrechte an einem fiktiven Gut. Es gibt **drei** verschiedene Pakete, welche das Nutzungsrecht am fiktiven Gut beschreiben. Das Paket „Beide Perioden" (im folgenden Screenshot mit 40 Punkten bewertet) erlaubt die Nutzung des Gutes für zwei Perioden. Paket „Periode 1" (19 Punkte) erlaubt die Nutzung in Periode 1, Paket „Periode 2" (21 Punkte) in Periode 2. Die Wertschätzungen für die Pakete werden zu Beginn jeder Runde vom Computer zufällig für alle Bieter neu ausgelost (siehe weiter unten für Details). Sie können nur Ihre eigene Wertschätzung sehen. Die Wertschätzungen der anderen Bieter können davon abweichen.

CA

<u>Die Rollen:</u>

In diesem Experiment sind alle Bieter in zwei unterschiedliche Rollen eingeteilt. In jeder Auktion gibt es *zwei* **flexible Bieter** und *einen* **unflexiblen Bieter**.

- **Flexible Bieter** können auf alle drei Pakete bieten.
- **Unflexible Bieter** können nur auf Paket „Beide Perioden“ bieten.

Ihre Rolle wird Ihnen am Anfang des Experiments auf dem Bildschirm mitgeteilt. Die Rollenverteilung bleibt über das gesamte Experiment gleich.

Die Wertschätzungen werden nach dem folgenden Verfahren zufällig vom Computer bestimmt. Sie sind unabhängig von den Vorrunden und von allen anderen Bietern.

Wertschätzung des flexiblen Bieters: Die Wertschätzung für Paket „Beide Perioden“ ist immer 40. Zusätzlich wird eine zufällige Zahl X zwischen 0 und 40 bestimmt, um die Wertschätzung für Paket Periode 1 zu bestimmen**.** Dabei sind alle ganzen Zahlen zwischen 0 und 40 gleich wahrscheinlich. Die Wertschätzung für Paket Periode 2 ergibt sich dann als 40 - X. Ist X zum Beispiel 10, dann hat dieser Bieter eine Wertschätzung von 10 für Paket Periode 1 und von 30 (= 40-10) für Paket Periode 2.

Wertschätzung des unflexiblen Bieters: Es wird eine zufällige Zahl zwischen 45 und 55 gezogen, diese ist die Wertschätzung für Paket „Beide Perioden“**.** Alle ganzen Zahlen zwischen 45 und 55 sind gleich wahrscheinlich. Die Wertschätzungen für die beiden anderen Pakete sind 0.

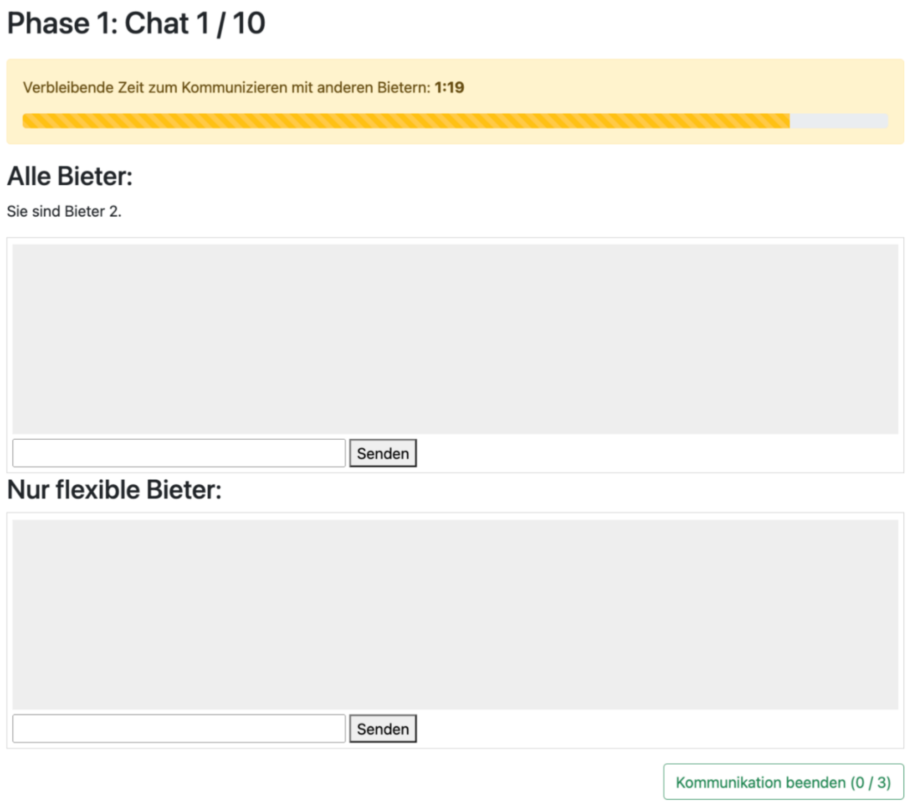
Wenn Sie ein Paket in der Auktion gewinnen, dann ergibt sich **Ihre Auszahlung** für diese Runde aus der **Differenz Ihrer Wertschätzung und Ihrem Gebot**.

Im Beispiel oben: Ihre Wertschätzung für Paket „Beide Perioden“ ist 40. Angenommen Sie haben 30 geboten und die Auktion gewonnen. Dann wäre Ihr Gewinn 10.

Als flexibler Bieter können Sie auch zwei Pakete gewinnen. In diesem Fall werden die Auszahlungen von beiden Paketen addiert. Gewinnen Sie die Auktion nicht, dann ist Ihre Auszahlung für diese Runde gleich 0.

Kommunikation

Vor jeder Auktion haben Sie die Möglichkeit, mit den anderen Bietern aus Ihrer Gruppe zu chatten. Dabei sehen Sie folgende Benutzeroberfläche:



Abhängig von Ihrer Rolle, sehen Sie entweder ein oder zwei Chatfenster. Ein flexibler Bieter hat die Möglichkeit, sowohl mit dem anderen flexiblen Bieter zu chatten als auch im allgemeinen Chat teilzunehmen. Der unflexible Bieter kann nur im Chat mit allen Teilnehmern chatten.

Hinweis: Im Chat gibt es gewisse Regeln. Es ist nicht erlaubt, sich selbst oder eine andere Person zu identifizieren. Außerdem sind beleidigende und unangebrachte Kommentare zu unterlassen. Ein Zuwiderhandeln führt zum Ausschluss vom Experiment und der Bezahlung.

<u>Ablauf der Auktion</u>

Direkt nach der Kommunikationsphase beginnt die Auktion, in der alle Bieter versuchen, ein oder mehrere Pakete zu gewinnen, indem sie passende Gebote abgeben. Ihr Gebot kann nicht höher sein als Ihre Wertschätzung für ein Paket.

Eine Auktion kann **maximal 60 Sekunden** dauern. Jedoch wird die Auktion vom Computer zu einem **zufällig gewählten Zeitpunkt zwischen Sekunde 20 und Sekunde 60 gestoppt**. Sie können dann zwar immer noch Gebote abgeben, jedoch werden diese Gebote nicht mehr gewertet. Erst nach Ende der Auktion erfahren Sie, wann die Auktion vom Computer beendet wurde und welche Gebote dementsprechend für das Gewinnen relevant sind. In den ersten 20 Sekunden der Auktion (dargestellt als gelber Balken, siehe unten) wird der Computer die Auktion nie beenden.

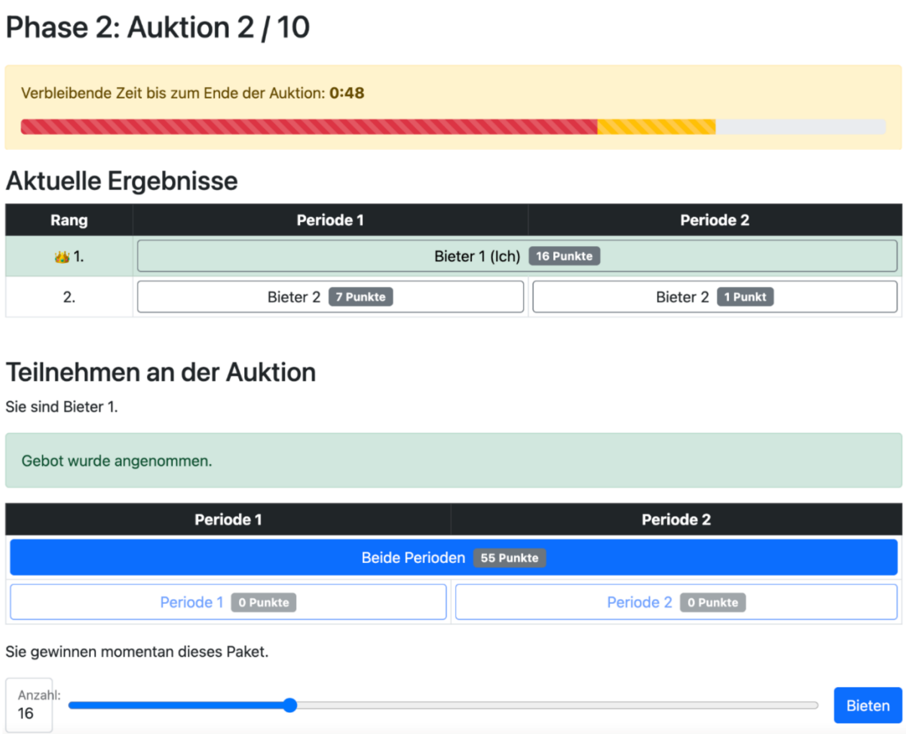
Jeder Bieter kann auf mehrere Pakete gleichzeitig bieten und immer neue Gebote abgeben, wenn das neue Gebot höher als das bestehende ist.

<u>Gewinnberechnung</u>: **Gewonnen hat das Gebot oder diejenigen Gebote, welche den Wert des gesamten Nutzungsrechts maximieren.** Das bedeutet, dass die Nutzungsdauer nur aufgeteilt wird, wenn die Summe der zwei Gebote auf Pakete Periode 1 und 2 höher ist als das Gebot auf Paket „Beide Perioden".

Beispiel: Angenommen, das Höchstgebot auf Paket „Beide Perioden" ist 40, das auf Paket Periode 1 ist 20 und das auf Paket Periode 2 ist 25. Dann bekommen die Bieter für Pakete Periode 1 und 2 den Zuschlag, da die Summe der Gebote mit 45 = 20 + 25 höher ist als das Gebot auf Paket „Beide Perioden" mit 40.

Sie werden die folgende Benutzeroberfläche im Experiment sehen.

CA



Erklärung der Benutzeroberfläche

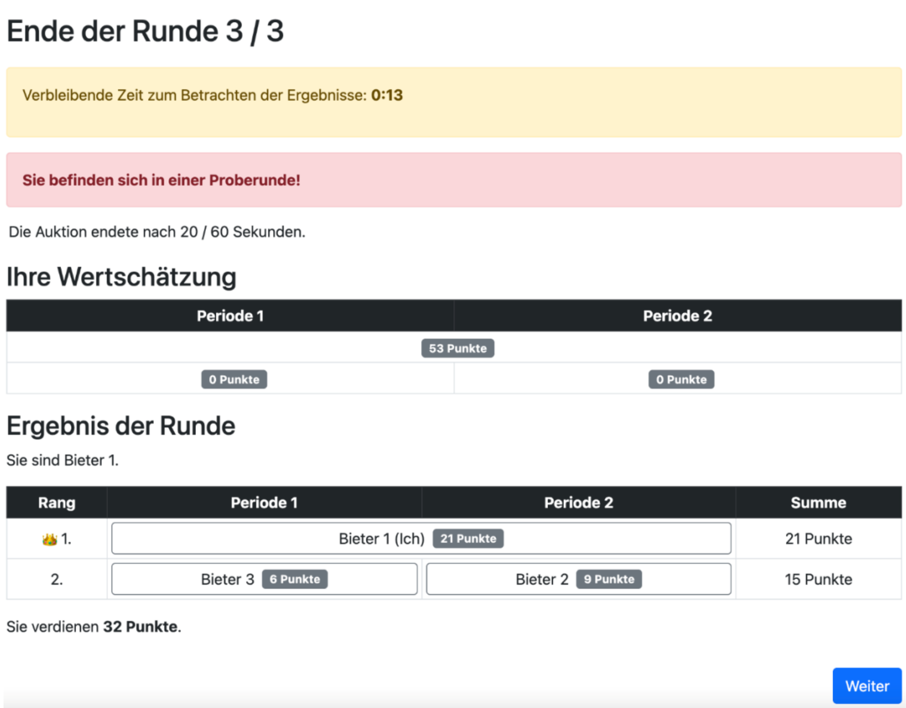
“Aktuelle Ergebnisse:” Hier sehen Sie das derzeitige Ergebnis der Auktion. In der ersten Zeile sehen Sie das aktuelle Gebot für Paket „Beide Perioden“, in der zweiten Zeile die jeweiligen Gebote für Perioden 1 und 2. In der Spalte “Rang” zeigt eine Krone an, welches Paket oder welche Pakete in der Auktion vorne liegen.

“Teilnehmen an der Auktion”: Hier können Sie Ihr Gebot eingeben. Klicken Sie dazu auf eines der verfügbaren Felder und nutzen Sie anschließend den Slider (oder die direkte Eingabe) und klicken Sie auf “Bieten”. Sie können den Slider nutzen, um das Gebot einzustellen oder das Gebot direkt eingeben, indem Sie auf die linke Box klicken.

Hinweis: Sobald Sie ein Paket ausgewählt haben, erscheint ein kleiner Hinweistext, der Ihnen vorschlägt, wie viel Sie bieten müssten, damit dieses Paket (eventuell zusammen mit einem anderen Gebot) vorne liegen würde.

Feedback Bildschirm:

Nach jeder Auktion bekommen Sie Feedback, wann die Auktion beendet wurde, wer die Gewinner waren und wie viel Sie verdient haben.



Ende der Runde 3 / 3

Verbleibende Zeit zum Betrachten der Ergebnisse: **0:13**

Sie befinden sich in einer Proberunde!

Die Auktion endete nach 20 / 60 Sekunden.

Ihre Wertschätzung

Periode 1	Periode 2
53 Punkte	
0 Punkte	0 Punkte

Ergebnis der Runde

Sie sind Bieter 1.

Rang	Periode 1	Periode 2	Summe
1.	Bieter 1 (Ich) 21 Punkte		21 Punkte
2.	Bieter 3 6 Punkte	Bieter 2 9 Punkte	15 Punkte

Sie verdienen **32 Punkte**.

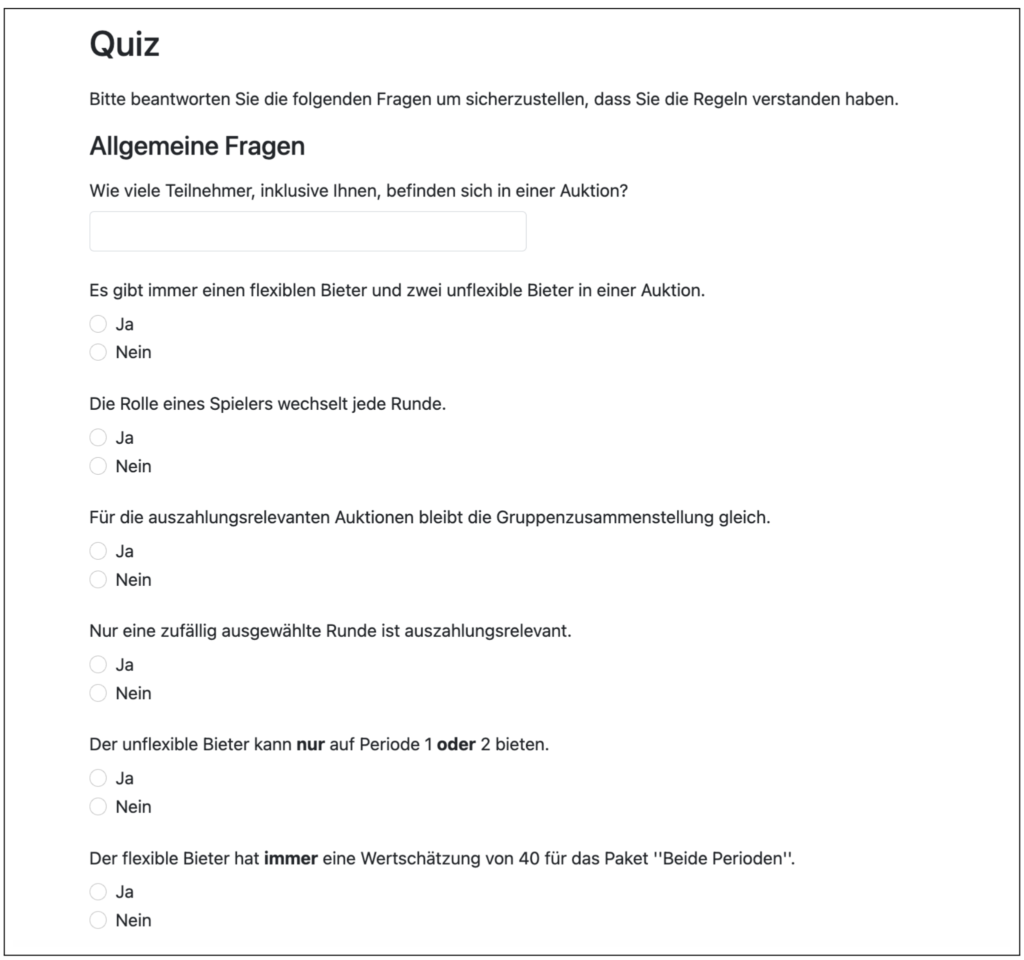
Weiter

Bezahlung:

Am Ende des Experiments wird zufällig eine Runde ausgewählt. Nur die Auszahlungen von dieser Runde werden in Euro umgerechnet und am Ende des Experiments in bar ausbezahlt.

D Experiment: Comprehension Quiz (German Original)

This section contains screenshots of the (German) comprehension quiz that we showed the subjects before the experiment (Figures 15–17). English translations are in Section F below. For each of the treatments, the quizzes differed only in the section "Regeln der Auktion" ("Auction Rules").



Quiz

Bitte beantworten Sie die folgenden Fragen um sicherzustellen, dass Sie die Regeln verstanden haben.

Allgemeine Fragen

Wie viele Teilnehmer, inklusive Ihnen, befinden sich in einer Auktion?

Es gibt immer einen flexiblen Bieter und zwei unflexible Bieter in einer Auktion.

- Ja
- Nein

Die Rolle eines Spielers wechselt jede Runde.

- Ja
- Nein

Für die auszahlungsrelevanten Auktionen bleibt die Gruppenzusammenstellung gleich.

- Ja
- Nein

Nur eine zufällig ausgewählte Runde ist auszahlungsrelevant.

- Ja
- Nein

Der unflexible Bieter kann **nur** auf Periode 1 **oder** 2 bieten.

- Ja
- Nein

Der flexible Bieter hat **immer** eine Wertschätzung von 40 für das Paket ''Beide Perioden''.

- Ja
- Nein

Figure 15: Screenshot of the Quiz 1/3 (in German)

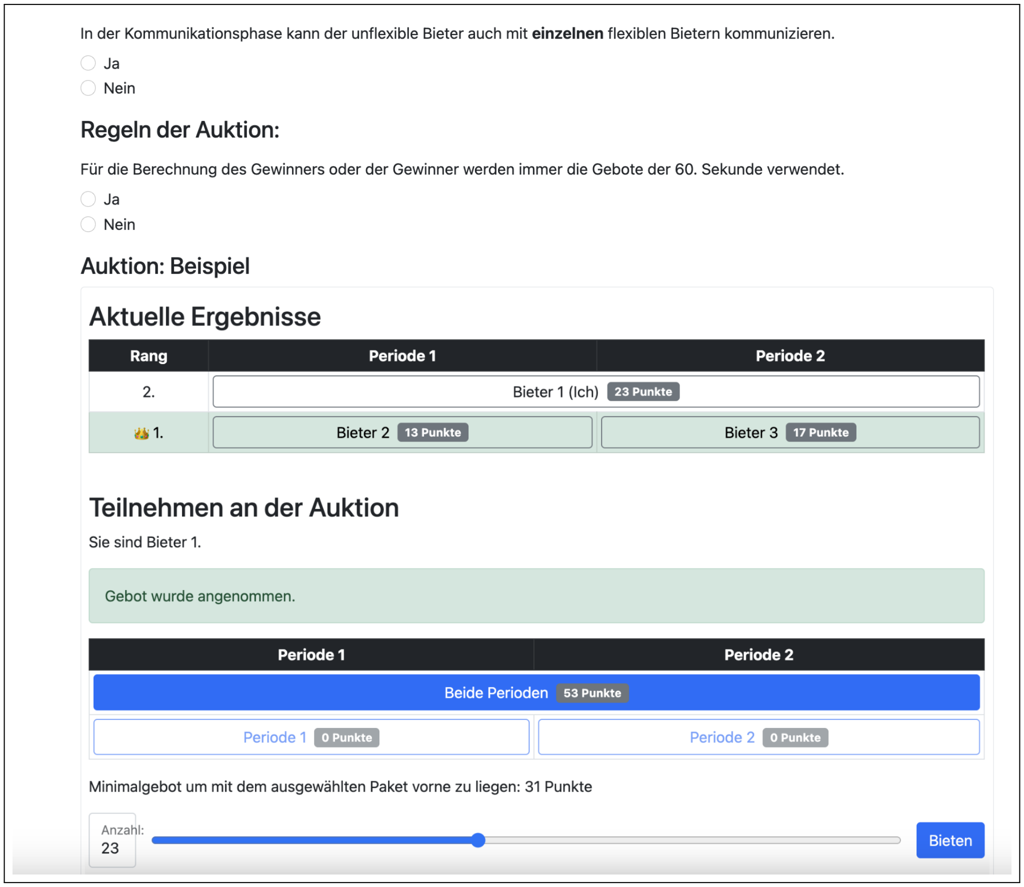


Figure 16: Screenshot of the Quiz 2/3 (in German)

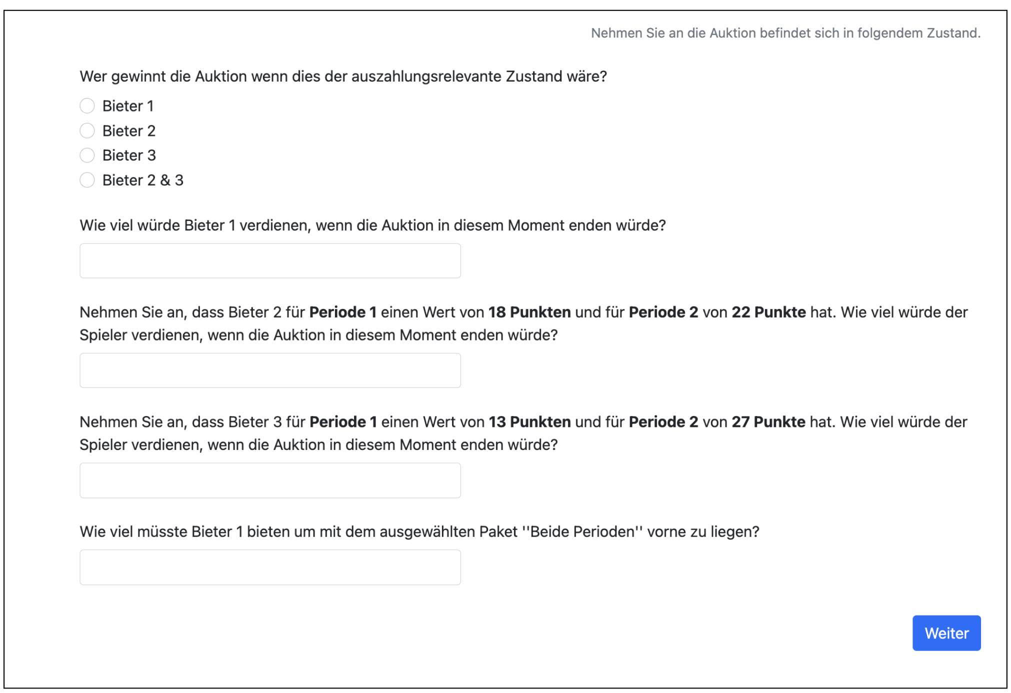


Figure 17: Screenshot of the Quiz 3/3 (in German)

E Experiment: Instructions (Translations)

This section contains the English translations of the instructions from Section C.

Instructions

Procedure of the experiment:

1. Read the instructions
2. Control questions for understanding
3. Practice auctions: 3 rounds
4. Auctions: 10 rounds
5. Questionnaire
6. Payment

Today they are taking part in a decision-making experiment. If you read the following explanations carefully, you can make money. The amount you receive depends on your decisions and the decisions of the other participants.

For the entire duration of the experiment, it is not allowed to talk to other participants. Violation of this rule will result in exclusion from the experiment and payment.

If you don't understand something, please look at this guide again or give us a hand signal. We will then come to you and answer your question personally.

During the experiment, we are not talking about euros, but about abstract **points**. The points you score during the experiment will be converted into euros as follows:

1 point = 2 €

At the end, you will receive the points relevant for the payout converted into euros and an additional €15 for your appearance in **cash**.

On the following pages, we explain the exact procedure of the experiment. After reading and understanding the instructions, answer the control questions at the end of the instructions that should help you understand the process better. The experiment does not begin until all participants are fully familiar with the course of the experiment and have answered the control questions correctly. The instructions are the same for all participants.

The Experiment: Overview

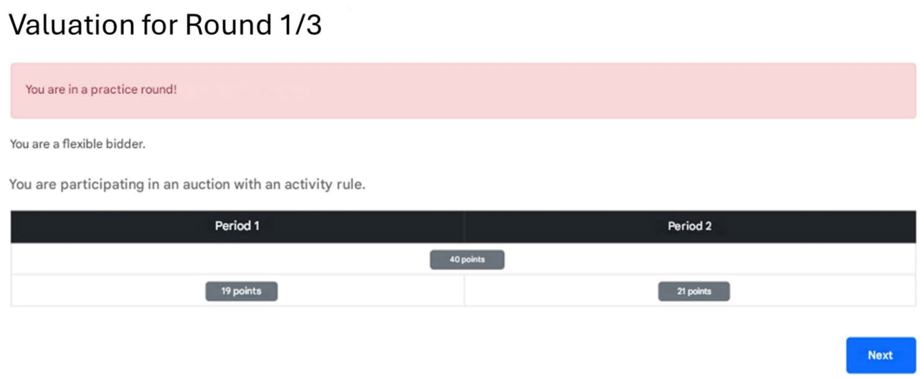
In this experiment, you will participate as **a bidder** in **auctions** for the right to use a fictitious good, which is divided into two periods. If you bid for a right of use, you will receive points. It is possible to buy the right of use for both periods (Period 1 *and* Period 2) or for one of the two periods.

They will be randomly divided into groups of **three** participants from this room for the auctions. So, each auction has **three** bidders. In total, you play ten ranked auctions (= rounds). Neither you nor the other participants learn anything about the identity of the other participants in the groups – neither before nor after the experiment.

Before the ten ranked auctions, you will take part in three practice auctions. Here you can familiarize yourself with the user interface. After the practice auctions, the groups will be reassembled once and will remain the same for all 10 ranked auctions.

The fictitious good:

In each auction, the participants bid for rights of use to a fictitious good. There are **three** different packages that describe the right of use of the fictitious good. The "Both Periods" package (rated with 40 points in the screenshot below) allows the use of the asset for two periods. Package "Period 1" (19 points) allows use in period 1, package "Period 2" (21 points) in period 2. The valuations for the packages are randomly redrawn by the computer for all bidders at the beginning of each round (see below for details). You can only see your own valuation. The valuations of the other bidders may differ from this.



The roles:

In this experiment, all bidders are divided into two different roles. In each auction, there are *two* **flexible bidders** and *one* **inflexible bidder**.

- **Flexible bidders** can bid on all three packages.
- **Inflexible bidders** can only bid on the "Both Periods" package.

Your role will be communicated to you on the screen at the beginning of the experiment. The distribution of roles remains the same throughout the experiment.

The valuations are randomly determined by the computer according to the following procedure. They are independent of the preliminary rounds and of all other bidders.

Valuation of the flexible bidder: The valuation for package "Both periods" is always 40. In addition, a random number X between 0 and 40 is determined to determine the valuation for Package Period 1**.** All integers between 0 and 40 are equally likely. The valuation for package Period 2 then results as 40 - X. For example, if X is 10, then this bidder has a valuation of 10 for package Period 1 and of 30 (= 40-10) for package Period 2.

Valuation of the Inflexible Bidder: A random number between 45 and 55 is drawn, this is the Valuation for the "Both Periods" package**.** All integers between 45 and 55 are equally likely. The valuations for the other two packages are 0.

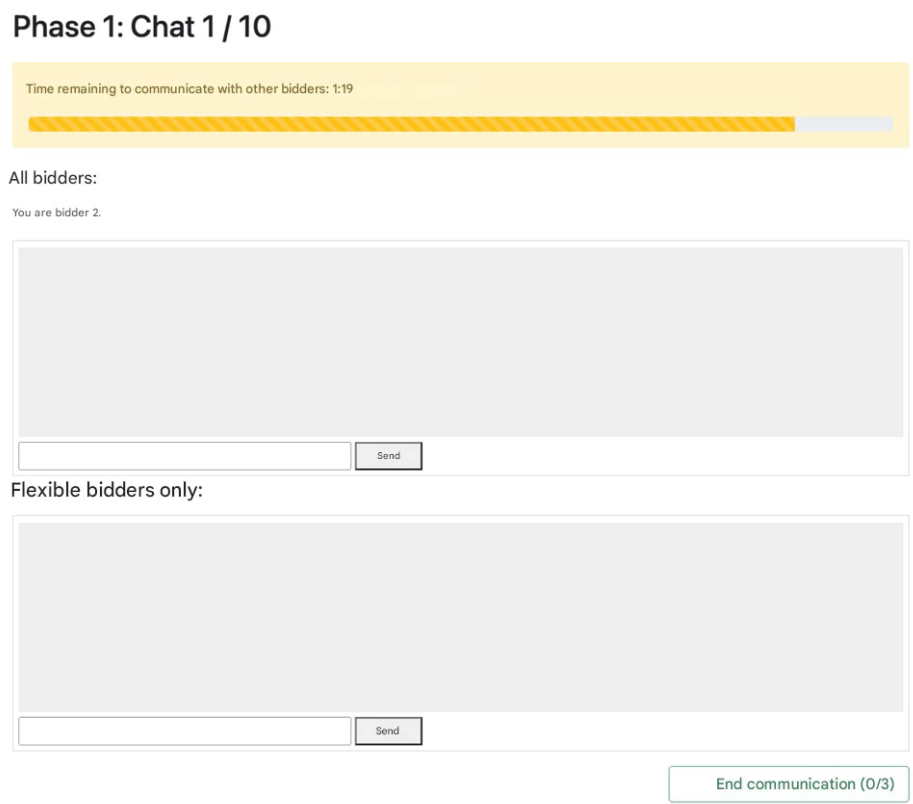
If you win a package in the auction, then **your payout** for that round will be the **difference between your valuation and your bid**.

In the example above, your valuation for the "Both Periods" package is 40. Then your profit would be 10.

As a flexible bidder, you can also win two packages. In this case, the payouts from both packages are added together. If you do not win the auction, then your payout for that round will be equal to 0.

Communication

Before each auction, you have the opportunity to chat with the other bidders in your group. You will see the following user interface:



Depending on your role, you'll see either one or two chat windows. A flexible bidder has the option to chat with the other flexible bidder as well as participate in general chat. The inflexible bidder can only chat with all participants in the chat.

Note: There are certain rules in chat. It is not allowed to identify yourself or any other person. In addition, insulting and inappropriate comments are to be avoided. Failure to do so will result in exclusion from the experiment and payment.

Auction Procedure

Immediately after the communication phase, the auction begins, in which all bidders try to win one or more packages by submitting matching bids. Your bid can't be higher than your valuation for a package.

An auction lasts at least **45 seconds**. However, each new bid in the last 10 seconds of the auction resets the timer (shown as a yellow or red bar) **back to 10 seconds**. This means that the auction does not end until no new bid is placed in the last 10 seconds.

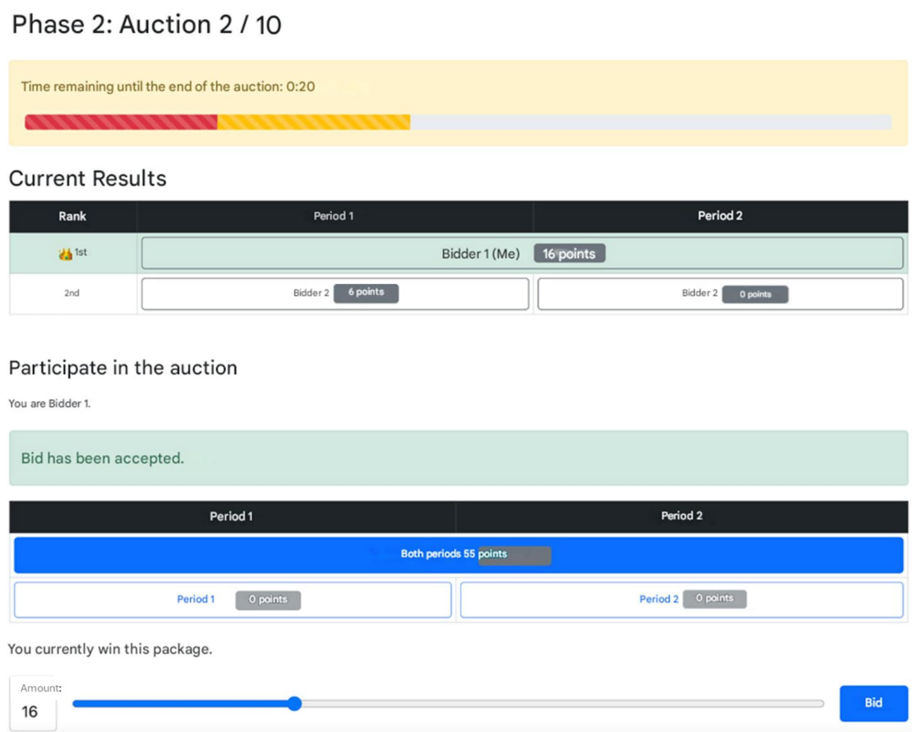
Each bidder can bid on several packages at the same time and always submit new bids if the new bid is higher than the existing one.

Profit calculation: **The winner is the bid or bids that maximize the value of the entire right of use.** This means that the usage time will only be split if the sum of the two bids on Period 1 and 2 packages is higher than the bid on both periods package.

For example, suppose the maximum bid on package "Both periods" is 40, that on package Period 1 is 20, and that on package Period 2 is 25. Then the bidders for packages Period 1 and 2 are awarded the contract, because the sum of the bids is higher at 45 = 20 + 25 than the bid for package "Both periods" at 40.

You will see the following UI in the experiment.

AC



Explanation of the user interface

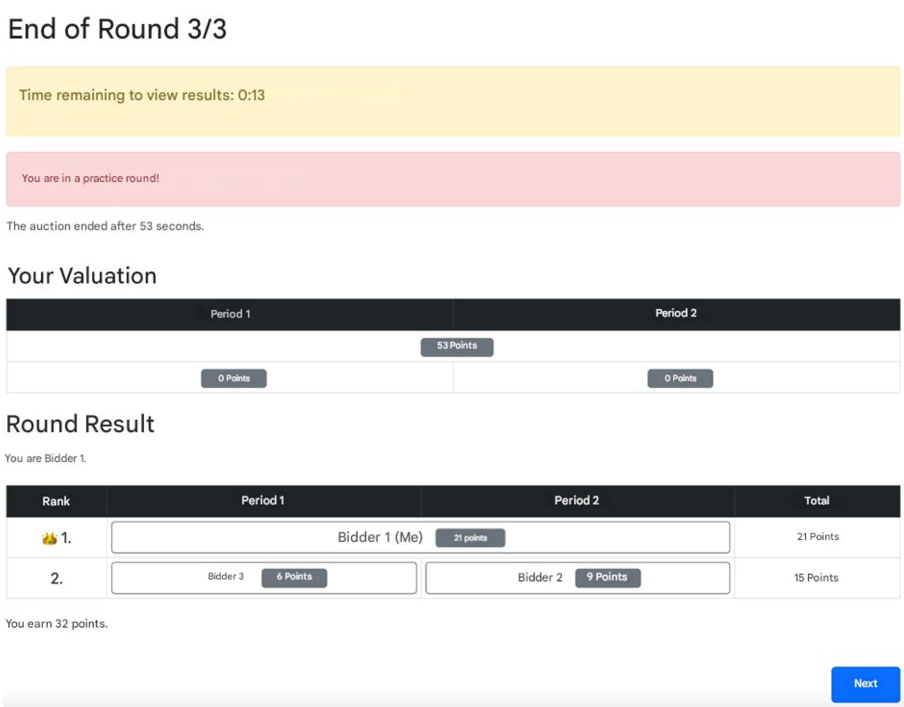
"Current Results:" Here you can see the current result of the auction. In the first row, you can see the current bid for the "Both periods" package, and in the second row, you can see the bids for periods 1 and 2. In the "Rank" column, a crown indicates which package or packages are ahead in the auction.

"Participate in the auction": Here you can enter your bid. To do this, click on one of the available fields and then use the slider (or direct entry) and click on "Bid". You can use the slider to set the bid or enter the bid directly by clicking on the box on the left.

Note: Once you have selected a package, a small hint text will appear suggesting how much you would have to bid for this package (possibly together with another bid) to be ahead.

Feedback Screen:

After each auction, you will receive feedback on when the auction ended, who the winners were, and how much you earned.



Payment:

At the end of the experiment, a round is randomly selected. Only the payouts from this round will be converted into euros and paid out in cash at the end of the experiment.

Instructions

Procedure of the experiment:

1. Read the instructions
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Today they are taking part in a decision-making experiment. If you read the following explanations carefully, you can make money. The amount you receive depends on your decisions and the decisions of the other participants.

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On the following pages, we explain the exact procedure of the experiment. After reading and understanding the instructions, answer the control questions at the end of the instructions that should help you understand the process better. The experiment does not begin until all participants are fully familiar with the course of the experiment and have answered the control questions correctly. The instructions are the same for all participants.

The Experiment: Overview

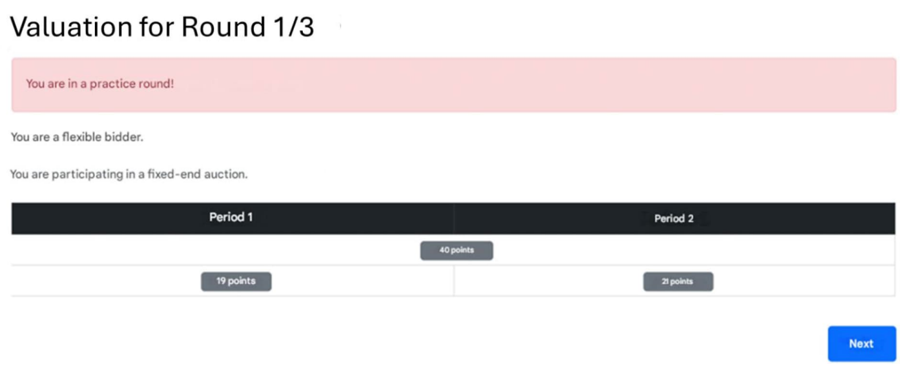
In this experiment, you will participate as **a bidder** in **auctions** for the right to use a fictitious good, which is divided into two periods. If you bid for a right of use, you will receive points. It is possible to buy the right of use for both periods (Period 1 *and* Period 2) or for one of the two periods.

They will be randomly divided into groups of **three** participants from this room for the auctions. So, each auction has **three** bidders. In total, you play ten ranked auctions (= rounds). Neither you nor the other participants learn anything about the identity of the other participants in the groups – neither before nor after the experiment.

Before the ten ranked auctions, you will take part in three practice auctions. Here you can familiarize yourself with the user interface. After the practice auctions, the groups will be reassembled once and will remain the same for all 10 ranked auctions.

The fictitious good:

In each auction, the participants bid for rights of use to a fictitious good. There are **three** different packages that describe the right of use of the fictitious good. The "Both Periods" package (rated with 40 points in the screenshot below) allows the use of the asset for two periods. Package "Period 1" (19 points) allows use in period 1, package "Period 2" (21 points) in period 2. The valuations for the packages are randomly redrawn by the computer for all bidders at the beginning of each round (see below for details). You can only see your own valuation. The valuations of the other bidders may differ from this.



<u>The roles:</u>

In this experiment, all bidders are divided into two different roles. In each auction, there are *two* **flexible bidders** and *one* **inflexible bidder**.

- **Flexible bidders** can bid on all three packages.
- **Inflexible bidders** can only bid on the "Both Periods" package.

Your role will be communicated to you on the screen at the beginning of the experiment. The distribution of roles remains the same throughout the experiment.

The valuations are randomly determined by the computer according to the following procedure. They are independent of the preliminary rounds and of all other bidders.

Valuation of the flexible bidder: The valuation for package "Both periods" is always 40. In addition, a random number X between 0 and 40 is determined to determine the valuation for Package Period 1**.** All integers between 0 and 40 are equally likely. The valuation for package Period 2 then results as 40 - X. For example, if X is 10, then this bidder has a valuation of 10 for package Period 1 and of 30 (= 40-10) for package Period 2.

Valuation of the Inflexible Bidder: A random number between 45 and 55 is drawn, this is the Valuation for the "Both Periods" package**.** All integers between 45 and 55 are equally likely. The valuations for the other two packages are 0.

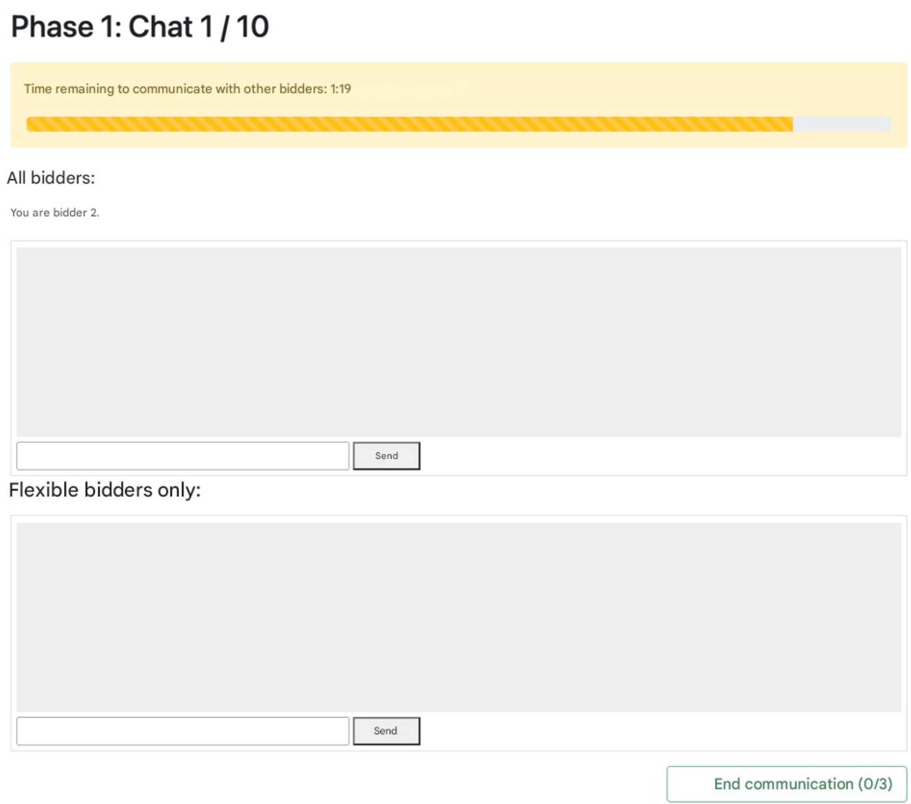
If you win a package in the auction, then **your payout** for that round will be the **difference between your valuation and your bid**.

In the example above, your valuation for the "Both Periods" package is 40. Then your profit would be 10.

As a flexible bidder, you can also win two packages. In this case, the payouts from both packages are added together. If you do not win the auction, then your payout for that round will be equal to 0.

Communication

Before each auction, you have the opportunity to chat with the other bidders in your group. You will see the following user interface:



Depending on your role, you'll see either one or two chat windows. A flexible bidder has the option to chat with the other flexible bidder as well as participate in general chat. The inflexible bidder can only chat with all participants in the chat.

Note: There are certain rules in chat. It is not allowed to identify yourself or any other person. In addition, insulting and inappropriate comments are to be avoided. Failure to do so will result in exclusion from the experiment and payment.

Auction Procedure

Immediately after the communication phase, the auction begins, in which all bidders try to win one or more packages by submitting matching bids. Your bid can't be higher than your valuation for a package.

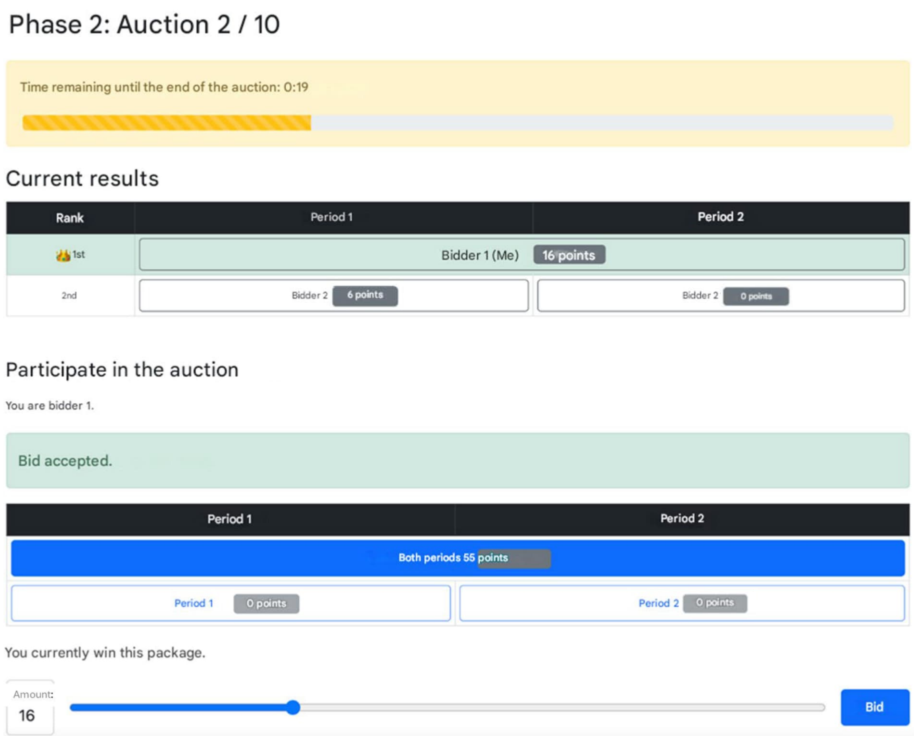
An auction lasts 60 **seconds** (the timer is shown as a yellow bar). Bids submitted later can no longer be considered.

Each bidder can bid on several packages at the same time and always submit new bids if the new bid is higher than the existing one.

Profit calculation: The winner is the bid or bids that maximize the value of the entire right of use. This means that the usage time will only be split if the sum of the two bids on Period 1 and 2 packages is higher than the bid on both periods package.

For example, suppose the maximum bid on package "Both periods" is 40, that on package Period 1 is 20, and that on package Period 2 is 25. Then the bidders for packages Period 1 and 2 are awarded the contract, because the sum of the bids is higher at 45 = 20 + 25 than the bid for package "Both periods" at 40.

You will see the following UI in the experiment.



Explanation of the user interface

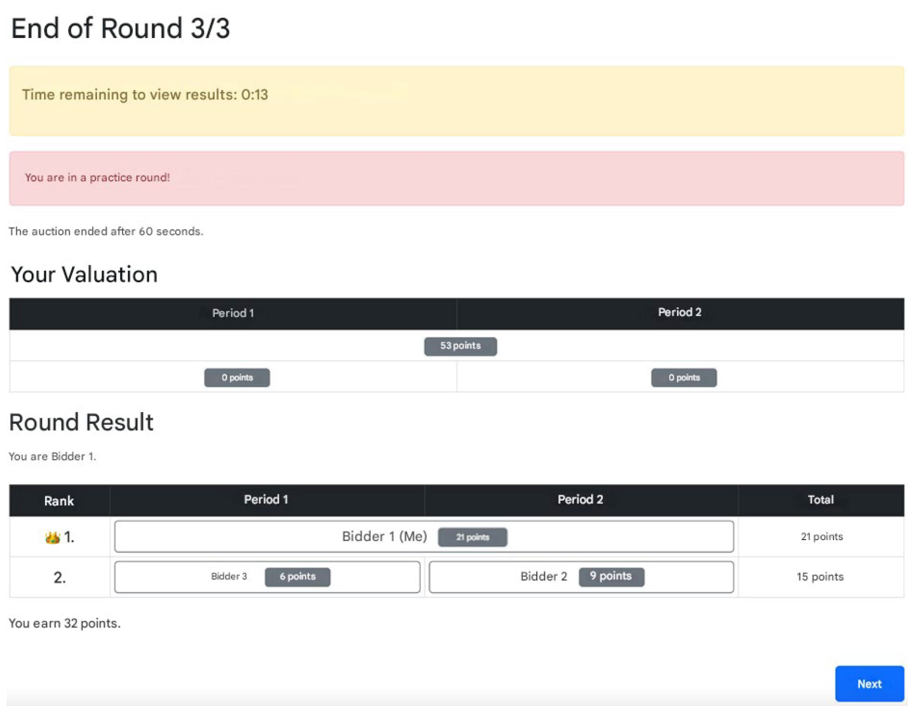
"Current Results:" Here you can see the current result of the auction. In the first row, you can see the current bid for the "Both periods" package, and in the second row, you can see the bids for periods 1 and 2. In the "Rank" column, a crown indicates which package or packages are ahead in the auction.

"Participate in the auction": Here you can enter your bid. To do this, click on one of the available fields and then use the slider (or direct entry) and click on "Bid". You can use the slider to set the bid or enter the bid directly by clicking on the box on the left.

Note: Once you have selected a package, a small hint text will appear suggesting how much you would have to bid for this package (possibly together with another bid) to be ahead.

Feedback Screen:

After each auction, you will receive feedback on when the auction ended, who the winners were, and how much you earned.



Payment:

At the end of the experiment, a round is randomly selected. Only the payouts from this round will be converted into euros and paid out in cash at the end of the experiment.

Instructions

Procedure of the experiment:

1. Read the instructions
2. Control questions for understanding
3. Practice auctions: 3 rounds
4. Auctions: 10 rounds
5. Questionnaire
6. Payment

Today they are taking part in a decision-making experiment. If you read the following explanations carefully, you can make money. The amount you receive depends on your decisions and the decisions of the other participants.

For the entire duration of the experiment, it is not allowed to talk to other participants. Violation of this rule will result in exclusion from the experiment and payment.

If you don't understand something, please look at this guide again or give us a hand signal. We will then come to you and answer your question personally.

During the experiment, we are not talking about euros, but about abstract **points**. The points you score during the experiment will be converted into euros as follows:

1 point = 2 €

At the end, you will receive the points relevant for the payout converted into euros and an additional €15 for your appearance in **cash**.

On the following pages, we explain the exact procedure of the experiment. After reading and understanding the instructions, answer the control questions at the end of the instructions that should help you understand the process better. The experiment does not begin until all participants are fully familiar with the course of the experiment and have answered the control questions correctly. The instructions are the same for all participants.

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- **Flexible bidders** can bid on all three packages.
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In the example above, your valuation for the "Both Periods" package is 40. Then your profit would be 10.

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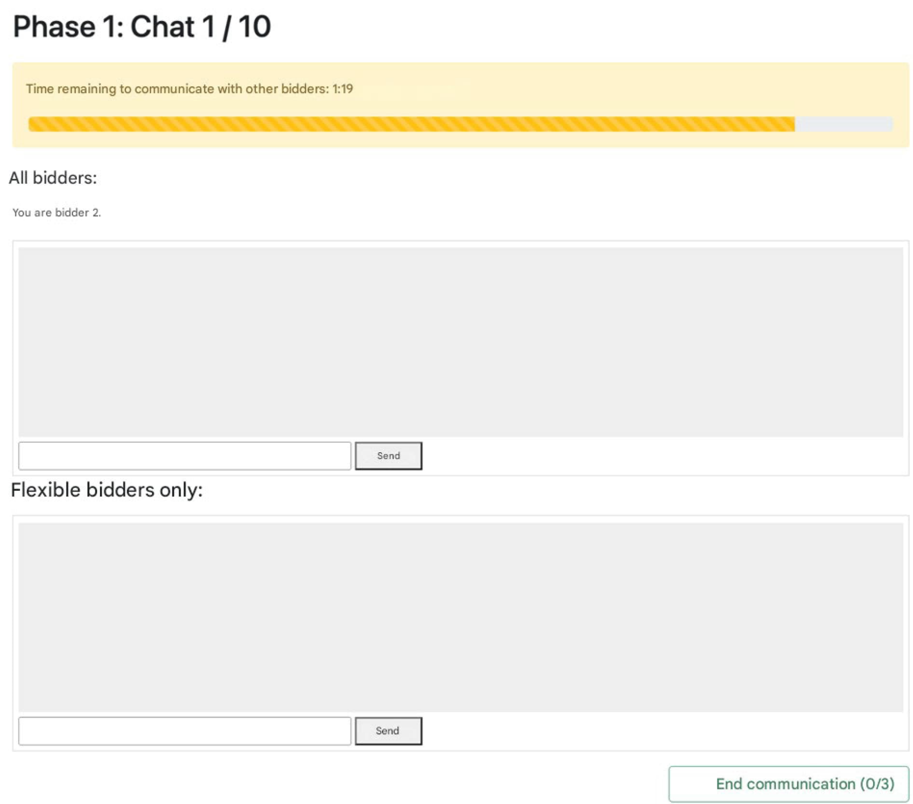
CA



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Note: There are certain rules in chat. It is not allowed to identify yourself or any other person. In addition, insulting and inappropriate comments are to be avoided. Failure to do so will result in exclusion from the experiment and payment.

Auction Procedure

Immediately after the communication phase, the auction begins, in which all bidders try to win one or more packages by submitting matching bids. Your bid can't be higher than your valuation for a package.

An auction can last **a maximum of 60 seconds**. However, the auction is stopped by the computer at a **randomly selected time between second 20 and second 60**. You can still place bids, but these bids will no longer be counted. Only after the auction has ended will you find out when the auction was ended by the computer and which bids are relevant for winning. In the first 20 seconds of the auction (shown as a yellow bar, see below), the computer will never end the auction.

Each bidder can bid on several packages at the same time and always submit new bids if the new bid is higher than the existing one.

Profit calculation: **The winner is the bid or bids that maximize the value of the entire right of use.** This means that the usage time will only be split if the sum of the two bids on Period 1 and 2 packages is higher than the bid on both periods package.

For example, suppose the maximum bid on package "Both periods" is 40, that on package Period 1 is 20, and that on package Period 2 is 25. Then the bidders for packages Period 1 and 2 are awarded the contract, because the sum of the bids is higher at 45 = 20 + 25 than the bid for package "Both periods" at 40.

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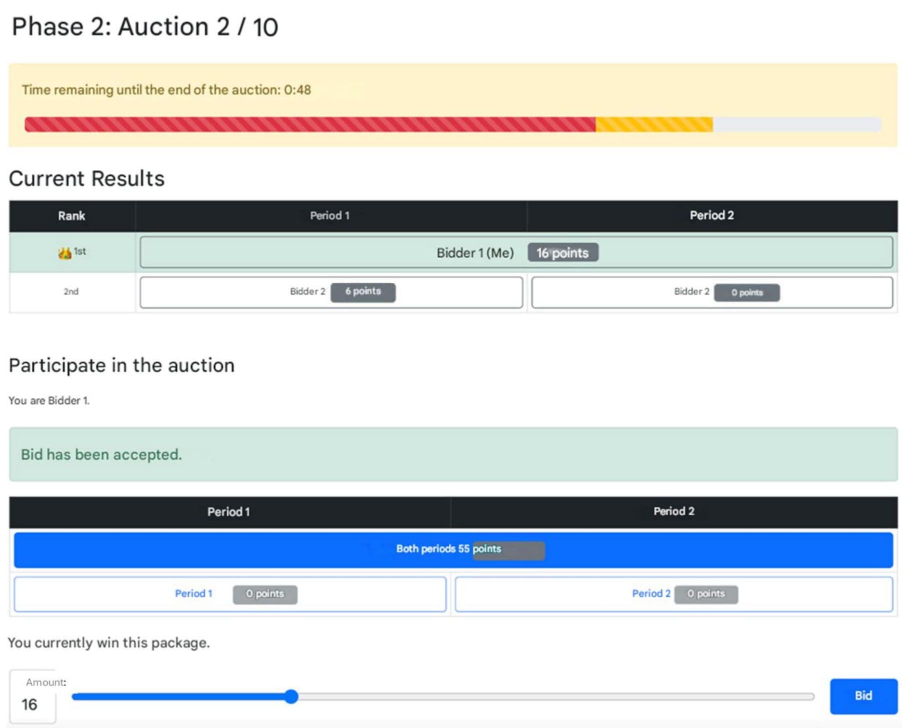

Explanation of the user interface

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Feedback Screen:

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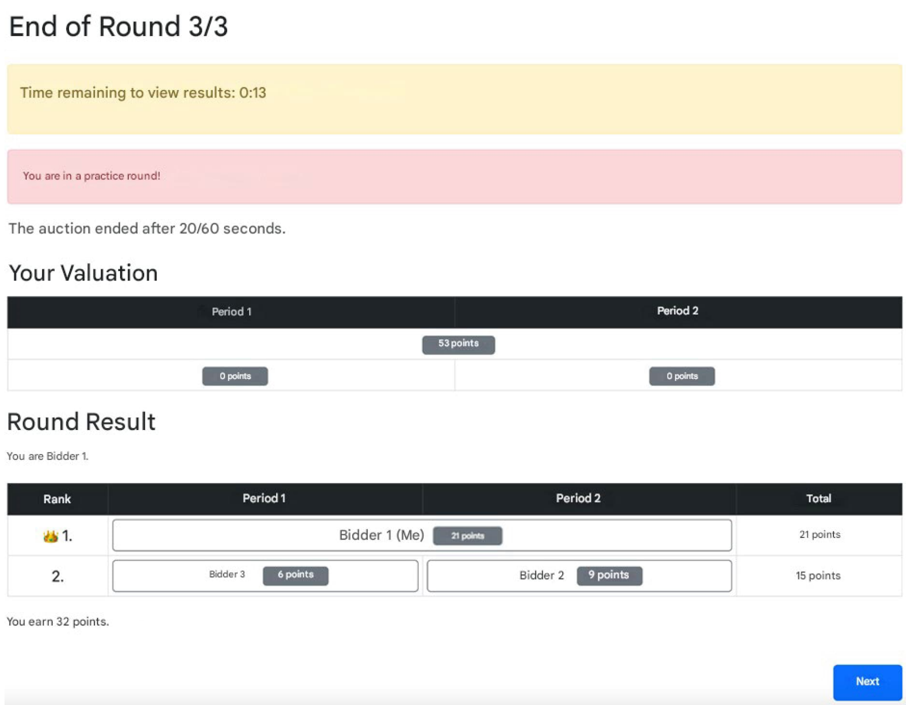

Payment:

At the end of the experiment, a round is randomly selected. Only the payouts from this round will be converted into euros and paid out in cash at the end of the experiment.

F Experiment: Comprehension Quiz (Translations)

Below are the translated screenshots of the comprehension quiz (Figures 18–20).

Quiz

Please answer the following questions to ensure you understand the rules.

General Questions

How many participants, including you, are in an auction?

There is always one flexible bidder and two inflexible bidders in an auction.

- Yes
- No

A player's role changes every round.

- Yes
- No

For payout-relevant auctions, the group composition remains the same.

- Yes
- No

Only one randomly selected round is payout-relevant.

- Yes
- No

The inflexible bidder can only bid on Period 1 or 2.

- Yes
- No

The flexible bidder always has a valuation of 40 for the "Both Periods" package.

- Yes
- No

Figure 18: Screenshot of the Quiz 1/3 (English translation)

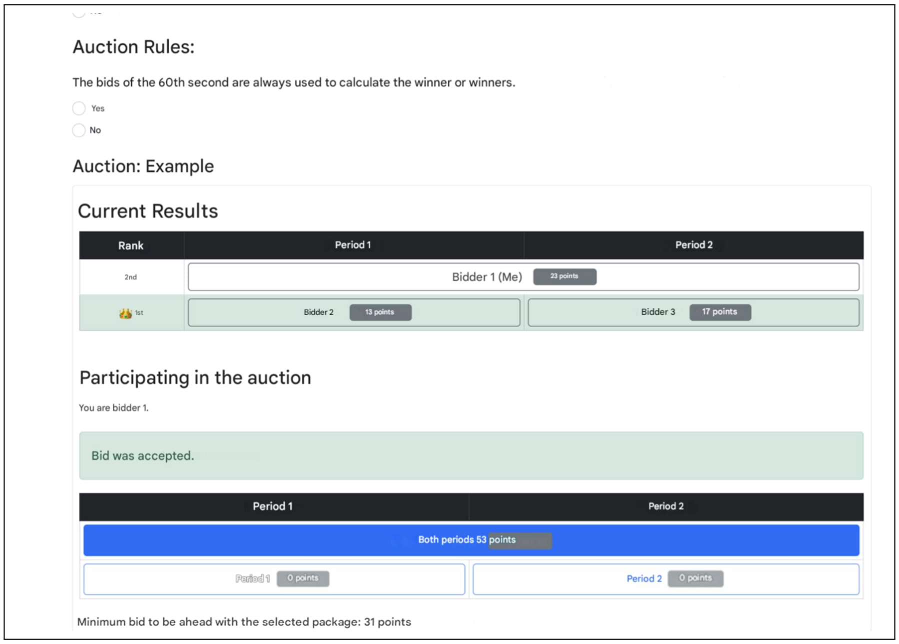

Figure 19: Screenshot of the Quiz 2/3 (English translation)

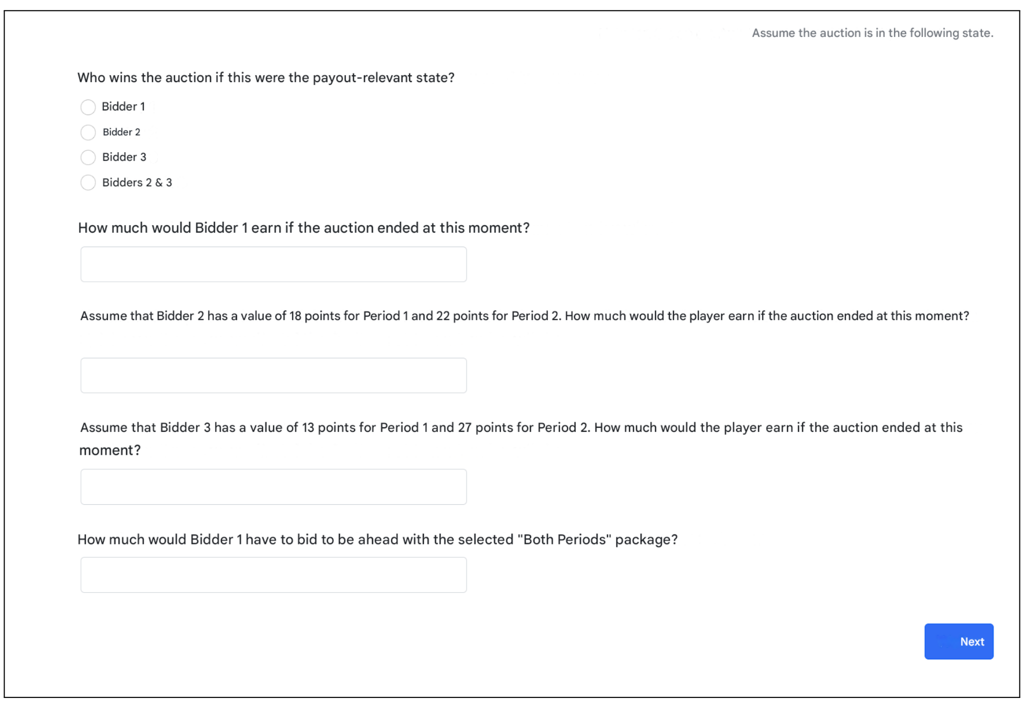

Figure 20: Screenshot of the Quiz 3/3 (English translation)