Expectations in first-price auctions*

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Abstract

Bids in independent private value first-price auctions consistently deviate from risk neutral symmetric equilibrium bids. To understand these deviations we present a novel experimental procedure which allows to study the formation of expectations separately from the determination of a best reply against these expectations.

We extensively test the internal validity of this setup. We find that deviations from Bayesian Nash equilibrium is not due to wrong expectations but due to deviations from a best reply.

Keywords: Experiments, Auction, Expectations.

(JEL C92, D44)

1 Introduction

Bidding behaviour in first-price auctions with independent private values has been thoroughly analysed theoretically and experimentally but not yet understood conclusively. Recent publications by Crawford and Iriberri (2007), Engelbrecht-Wiggans and Katok (2007), Filiz-Ozbay and Ozbay (2007),

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Morgan, Steiglitz, and Reis (2003), and Ockenfels and Selten (2005) reflect an increasing interest in this topic. Although expectations about other buyers' bidding behaviour play a crucial role in the theoretical analysis of equilibrium bidding, expectations about bids have not yet been measured separately from bids in experimental auctions. In this paper we introduce and test a new method to measure expectations for entire bidding strategies. This allows to disentangle expectation formation from best replies which, in turn, contributes to understanding why observed behaviour deviates from standard equilibrium theory.

Early experiments with first-price auctions by Coppinger, Smith, and Titus (1980) and Cox, Roberson, and Smith (1982) find that bidders consistently deviate from risk neutral symmetric Bayesian Nash equilibrium bids. There is overbidding for large valuations (Cox, Smith, and Walker, 1983, 1985, 1988) and underbidding for small valuations (see Kirchkamp and Reiß, 2004).

Risk aversion is a standard explanation for deviations from equilibrium bids. Alternative explanations include regret (see Filiz-Ozbay and Ozbay, 2007), spite (Morgan, Steiglitz, and Reis, 2003), and learning (Ockenfels and Selten, 2005; Neugebauer and Selten, 2006).

We find it remarkable that many of these approaches do not attack the expectation formation part of rational decision making. Instead, many approaches concentrate on modifying either the utility function or the best reply process. The utility function is modified by introducing risk aversion, concerns for inequality or regret. The best reply process is replaced by various learning mechanisms.

In this article we look at another facet of rational decision making: the formation of expectations. When choosing a strategy a rational bidder first needs expectations about the opponents' bidding behaviour. Then, given these expectations, the own bidding function is determined as a best reply. Equilibrium is reached when all bidders form correct expectations about the bidding behaviour of their opponents and all bidders play a best reply.

Deviations from equilibrium bids can be related to two causes: Bidders either form different expectations about their opponents' bids or bidders choose a reply which differs from the risk neutral best reply. The aim of this paper is to distinguish between these two effects. Knowledge about the source of deviations from equilibrium allows to better assess alternative equilibrium concepts; e.g., the introduced method provides a direct test of level k auction theory as recently suggested by Crawford and Iriberri (2007).

In the following we describe an experiment that allows us to elicit bidding functions and expectations separately in a simple and natural way. We use the strategy method to observe bidding functions in a way similar to Selten and Buchta (1999), Güth, Ivanova-Stenzel, Königstein, and Strobel (2003), Pezanis-Christou and Sadrieh (2003), Kirchkamp and Reiß (2004), and Kirchkamp, Poen, and Reiß (2004). Our previous experience with this method, e.g. in Kirchkamp, Poen, and Reiß (2004) and Kirchkamp and Reiß (2004), gives confidence that bidding behaviour that is observed with the strategy method is very similar to the behaviour observed with alternative methods. The strategy method allows us, however, to observe bidding functions in much more detail. We then show how such a setup can be modified to also observe expectations.

In this paper we study both steps of reasoning simultaneously: expectations together with strategies. An alternative approach would be to study expectations and strategies each in isolation: In a first experiment participants would only form expectations. The process of determining a best reply would be controlled and fixed, e.g. through a computerised mechanism. In a second experiment participants would only choose strategies. Expectations would be controlled through computerised opponents which follow a fixed and known strategy.

The second step of such an exercise has already received attention in the literature. Walker, Smith, and Cox (1987) study an experiment where participants play against a computerised opponent. However, since participants are not informed about the computerised bidding function, a comparison of bids with best replies is not possible. Neugebauer and Selten (2006) explore a scenario where bidders with a fixed valuation play against computerised opponents with a known distribution of bids. This setup allows to compare participants' strategies with best replies. Importantly, Neugebauer and Selten (2006) do not observe expectations. Dorsey and Razzolini (2003) study the behaviour of bidders against a computerised bidder with a known bidding function. They find that bids change if this game is presented as a lottery instead of an auction. But also Dorsey and Razzolini (2003) do not observe expectations.

It may be possible to complement Neugebauer and Selten (2006) or Dorsey and Razzolini (2003) by designing an experiment where participants form only expectations and where best replies are fixed. However, implementing general best reply functions in an experiment is hard and requires some computing power. Furthermore, explaining such a mechanism to participants in an experiment is not trivial. In our experiment we use a design where participants carry out both steps themselves such that we observe both steps simultaneously.

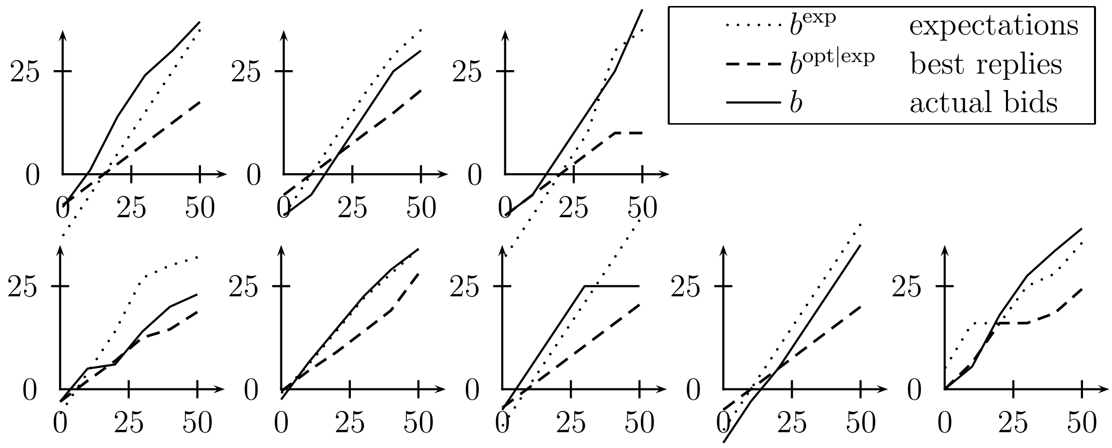
Our approach is similar to Costa-Gomes and Weizsäcker (2004) who observe actions and expectations simultaneously in 3×3 normal form games. Their experiments suggest that strategies are typically not in line with expectations while expectations seem to resemble actual strategies fairly well.

In comparison to Costa-Gomes and Weizsäcker (2004), we do not only analyse a different type of game (an auction with incomplete information and infinitely many actions instead of a 3×3 game with complete information and a finite number of actions), we also look at a symmetric game while Costa-Gomes and Weizsäcker use asymmetric games. The advantage of using asymmetric games is that participants have to think separately about their own and their opponent's strategy. The disadvantage of using asymmetric games, when these games are complex, is that participants have to understand two complex situations simultaneously. In particular, asking for strategies and expectations in an asymmetric auction might overburden participants. Hence, we decided to use the simpler, symmetric setup for our auctions. The disadvantage is that we have to take extra care in checking whether participants distinguish between their own and their opponents' strategies. The advantage of using a symmetric auction is that the already complex setup remains still manageable.

We briefly summarise the equilibrium model in section 2. The experimental treatments are discussed in section 3 and internal validity of our setup is checked in section 4. We present results in section 5 and conclude in section 6.

2 Model

We will study a private value first-price sealed-bid auction with two bidders i and j. Bidders' valuations x_i and x_j are independently distributed according to a distribution function $F()$ which is the same for each bidder. The derivation of risk neutral symmetric Bayesian Nash equilibria is standard and shown to introduce the notation. We will use risk neutral equilibria as a benchmark here and we will use an experimental setup that eliminates at least a substantial part of the risk that bidders face in auctions. Bidder i with valuation x_i expects the opponent to follow a monotonically increasing bidding function $b^{\exp}(x_j)$ with inverse $b^{\exp(-1)}(\cdot)$. If bidder i makes a bid $b(x_i)$ then this bidder gains $x_i - b(x_i)$ with probability $F(b^{\exp(-1)}(b(x_i)))$ and the expected profit is $u = (x_i - b(x_i)) \cdot F(b^{\exp(-1)}(b(x_i)))$. Bidders choose their individual bidding function b_i to maximise u given their expected opponents' bidding function $b^{\exp}$. It is straightforward to show (Vickrey,



Expectations, best replies and bids are for eight bidders in period 7 of an experiment on 12 May 2005.

FIGURE 1: Examples for expectations, best replies, and bids in the experiment

1961) that if $F()$ is a uniform distribution over some interval $[0, \bar{x}]$ both bidders have a symmetric bidding function

$$b^*(x) = \frac{1}{2}x \tag{1}$$

in the symmetric equilibrium. We should note that, while there are auction situations where further asymmetric equilibria exist, the unique equilibrium in the introduced auction model is symmetric (Maskin and Riley, 2003).

In the above derivation of equilibrium bids we decompose the reasoning of an individual into two steps. First bidders form expectations b^{exp} about the bidding function of their opponent. In the risk neutral Bayesian Nash equilibrium $b^{\text{exp}} = b^*$. Then bidders determine a best reply $b^{\text{opt|exp}}$ against these expectations and play this best reply. In equilibrium also $b^{\text{opt|exp}} = b^*$. Figure 1 shows some examples of expected opponent's bidding functions b^{exp} from our experiment together with the best reply $b^{\text{opt|exp}}$, and the bids b actually taken in the experiment. The examples show a general property: In the experiment bids b, expectations b^{exp}, and best replies $b^{\text{opt|exp}}$ typically do not coincide.

In section 3 we describe an experiment that allows us to observe the two steps of this decision process, i.e. the expectations b^{exp} (which define $b^{\text{opt|exp}}$) together with actual bids b. If we can observe both elements of decision-making, we can determine where the decision process of expectation formation and determining a best reply breaks. We will be able to distinguish between bidders who just form expectations which are systematically wrong (i.e. $b^{\text{exp}} \neq b$) but whose best replies against these expectations are correct and bidders with correct expectations but bids which are not best replies (i.e. $b \neq b^{\text{opt}|\text{exp}}$). With this exercise we do not aim to provide a complete and correct description of the thought process of real individuals. We are following the structure of equilibrium derivation within the context of expected utility theory, hence we can only find out where the standard equilibrium model of bidding behaviour provides a good approximation of human behaviour and where it does not. By decomposing this model into two steps we can, however, learn more than by only observing bids without expectations.

Crawford and Iriberri (2007) develop a model of level k thinking in auctions. In their model the simplest player, the $L0$ player, is the starting point of a player's strategic thinking. If this player is 'random', the player chooses all bids between the smallest possible valuation and the highest possible valuation with equal probability. If this player is 'truthful', the player always bids the own valuation. With our distribution of valuations both such types have the same distribution of bids and the best reply $L1$ against an $L0$ player happens to be the equilibrium bid given by equation (1). Thus, our experiment allows to distinguish between $L0$, $L1$, and $L2$ and higher order players. $L0$ players reveal themselves by choosing all bids from the possible range with equal probability in their own bidding function. $L1$ players do the same for their expectations but choose a best reply against $L0$ (which coincides with the equilibrium bid). $L2$ and higher order players have equilibrium expectations and equilibrium bids.

3 Experimental setup

In the experiment we want to distinguish between bids and expected opponent's bids. To do this, we compare three treatments:

- In one treatment we only elicit bids. This is our baseline treatment which we also call the 'no expectations' treatment. The only payoff in the treatment is the profit in the auctions.
- In one treatment we elicit bids and expectations. We call this the 'expectations' treatment. The payoff in this treatment is the profit in the auctions and a reward for precision of expectations.
- In one treatment we elicit bids and expectations and give feedback about the precise bidding function of the opponents. We call this the 'expectations with info' treatment. As in the previous treatment the payoff in this treatment is the profit in the auctions and a reward for precision of expectations.

treatment	independent observations	participants
no expectations	36	330
expectations	8	74
expectations w. info	11	102

Table 1: Overview of treatments

Experiments were conducted between 12/2003 and 05/2005 in the experimental laboratory of the SFB 504 in Mannheim and in the experimental laboratory MaXLab in Magdeburg. A total of 506 subjects participated in these experiments. The average profit of a participant was 12.31€ with a standard deviation of 5.91€. Table 1 gives an overview. A detailed list of the sessions is provided in appendix A, the experimental procedure is described in appendix B. The software we used was z-Tree Version 3α (the final version is documented in Fischbacher, 2007). In each treatment subjects first received written instructions, then they answered a quiz on the computer screen to make sure that they understood the instructions. Thereafter they played twelve rounds of the actual experiment. In each of these rounds participants were matched randomly in groups of two. Each group then participated in five simultaneous auctions. All treatments concluded with a questionnaire and the payment of subjects in cash.

Input of bidding functions: This stage was common to all treatments. Subjects would submit a bid function for a range of valuations from 50 to 100. When we present results below we will always consider normalised valuations where the valuation lies in the interval $[0, 50]$. A typical input screen for the no expectation treatment is shown in figure 2. A typical input screen for the two treatments with expectations is shown in figure 3.

In each round participants enter bids for six valuations which are equally spaced between 50 and 100. Bids for all other valuations are interpolated linearly.

Auction feedback: When all participants have determined their bidding functions they move to the auction feedback stage. In this stage we play five independent auctions, i.e. we draw five random and independent valuations for each participant. In each of these five independent auctions the winner is determined and the profit of each player is calculated. The sum of the profit of these five auctions is the total auction profit from this round. We

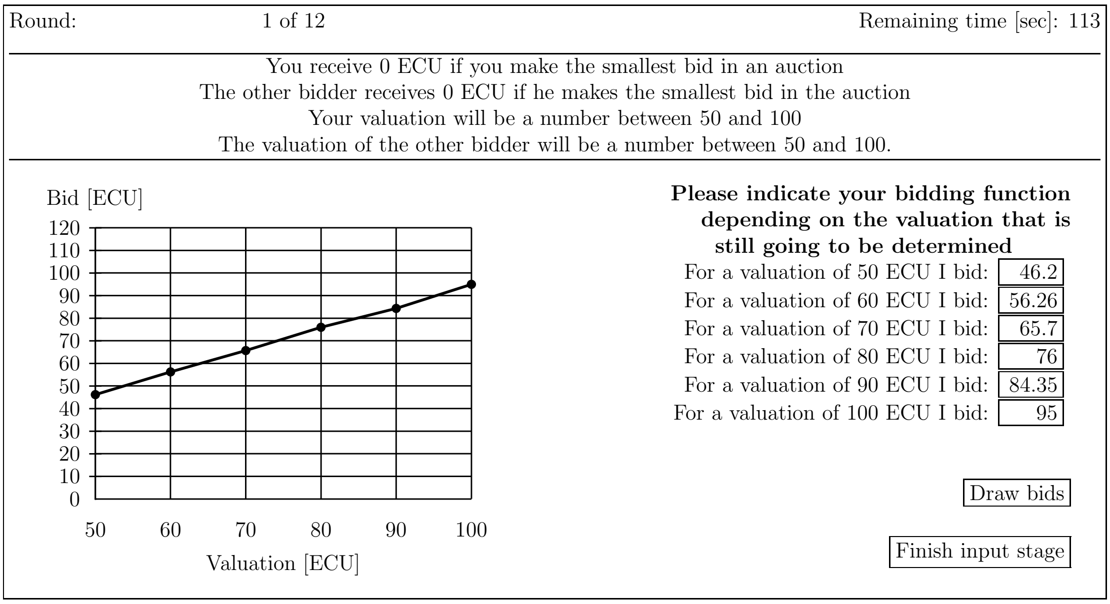


FIGURE 2: Stage 1: A typical input screen in the 'no expectations' treatment (translated into English)

play five auctions for two reasons: First, using several auctions should focus players to think carefully about all parts of their bidding function. Second, and more importantly, using several auctions helps us to reduce a substantial part of the risk. Kirchkamp, Reiß, and Sadrieh (2006) systematically explore the approach of using several simultaneous auctions with a given bidding function and find that using more auctions indeed makes bidders behave in a more risk neutral way. They do not find a big difference between using 5 and 50 auctions. To keep things simple we rely on only 5 auctions in this experiment. A typical feedback screen is shown in figure 4.

Expectation feedback: In the expectation treatments players get feedback about their expectations in the last stage of each round.

- In the baseline treatment the last screen only shows the total payoff of the current round.
- The last screen of each period of the expectation treatment screen shows on the left a graph with the expected bid. On the right a small table summarises the auction profit, the average difference between the expected bid and the actual bid, and the total payoff. The screen looks similar to the one shown in figure 5, except that it displays only the player's own expectation and not the actual bidding function of the

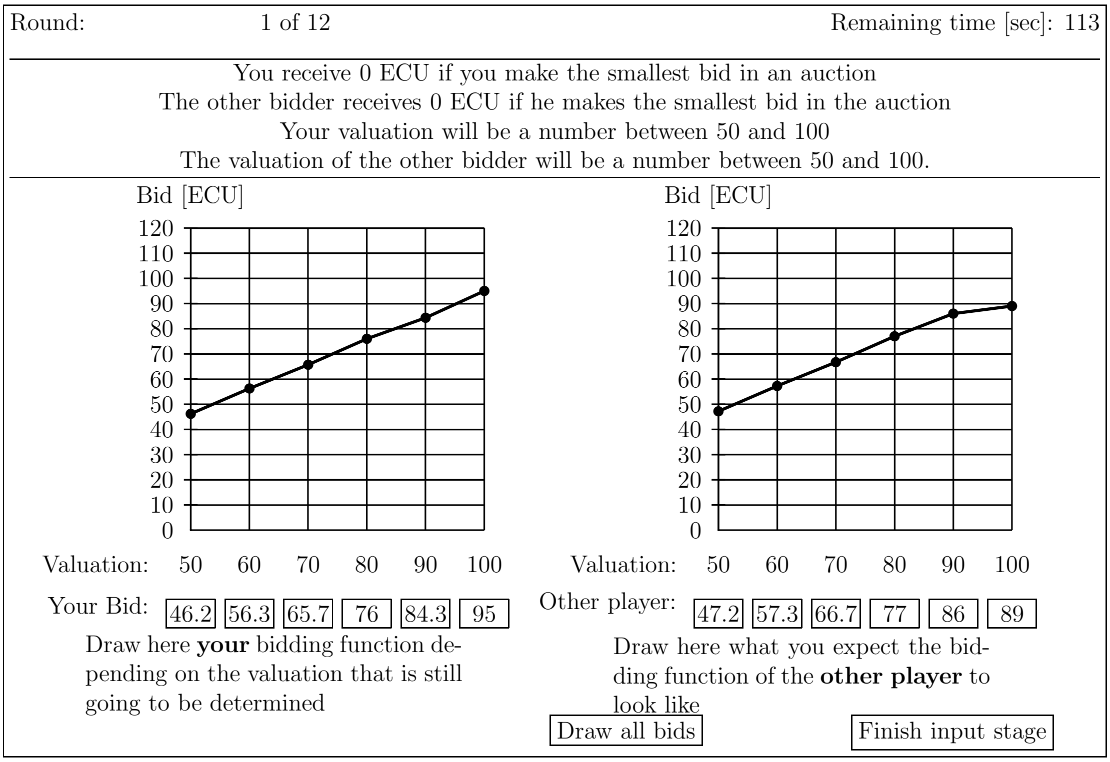


FIGURE 3: Stage 1: A typical input screen in the two 'expectations' treatments (translated into English)

opponent.

- The last screen of each period of the expectation treatment with info is shown in figure 5. A graph shows the expected bid and, additionally, also the actual bid of the opponent. As in the other treatment on the right a small table summarises the auction profit, the average difference between the expected bid and the actual bid, and the total payoff.

To pay participants for correct expectations in the expectation treatments we use the average of absolute differences between the actual bid of the opponent and the expected bid at the six points where bids and expectations were made.

$$\frac{1}{6} \sum_{x \in \{50,60,70,80,90,100\}} |b_x - b_x^e|$$

This average mistake is multiplied with a conversion factor of 0.3 and subtracted from the auction profit.

Point expectations In the above discussion we have made the implicit assumption that individuals expect their opponents to have one specific bidding function

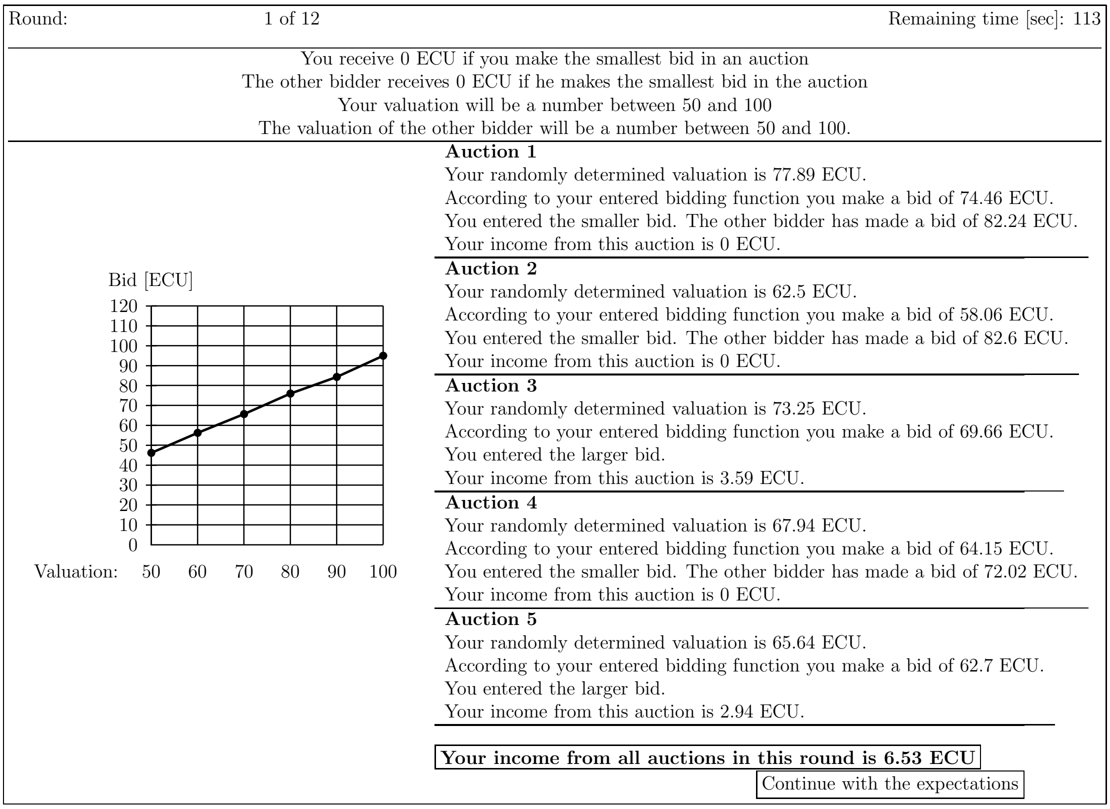


FIGURE 4: Stage 2: A typical feedback screen (translated into English)

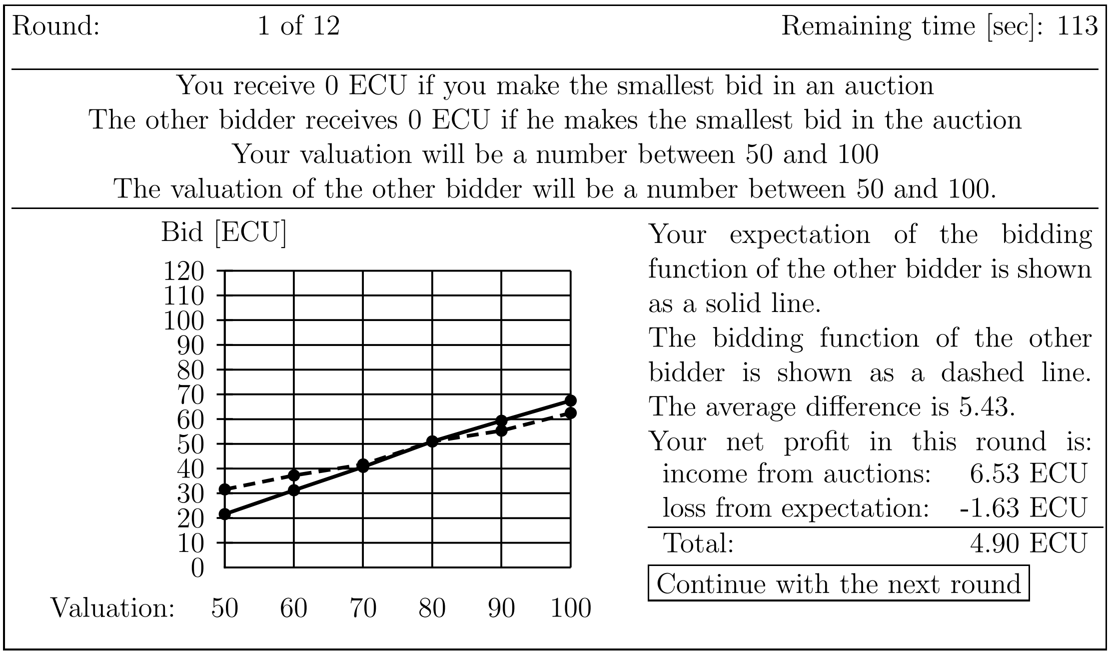


FIGURE 5: Stage 3: Expectation feedback in the expectation with info treatment

b^{exp}. We will call this a point expectation. What, if a player is uncertain about the bidding function of the opponent? A player might, e.g., expect to face an opponent with a bidding function b_1^{exp} with probability $\frac{1}{2}$ and to face an opponent with another bidding function b_2^{exp} again with probability $\frac{1}{2}$. A player might have an entire distribution over the space of all opponent's bidding functions in mind. How should such a player behave in our experiment? Since we are paying players according to their absolute deviations from the opponent's bidding function, players should report as expectations a least absolute deviation estimator, which is the median expected bid. When bidding under uncertainty about the opponent's bids, bidders are only interested in the distribution over their opponent's bids. An uncertain bidder who does not know the opponent's bids faces the same situation as a certain bidder who plays against the average bidding function (where the averages are taken along the opponent's bids). Thus, as long as the difference between median and mean bidding functions is small, the problem should be small. To assess the size of the problem at least approximately, let us assume that bidders apply the true distribution of bidding functions. Indeed, this distribution has a small negative skew. Medians are smaller than means by about 1.8% of the range of valuations (the size of the deviation does not depend much on the valuation). Thus, any deviation between reported expectations and bids of that magnitude is still perfectly rational. We will, however, find that deviations are substantially larger.

Even if mean expected bids deviate substantially from median expected bids the incentive to hedge is small. The loss for reporting other than median expectations and optimising against other than mean expectations is large, and the profit from hedging is very low unless the distribution is extremely asymmetric and participants are very risk averse. Hence, we do not expect hedging to be a problem. In the following we will disregard the problem of distributions of expectations and assume that bidders have point expectations of opponent's bidding functions.

4 Internal validity

Given the novelty of our experimental design we have to check whether we actually measure what we intend to measure. Does participants' behaviour converge during the experiment, have participants carefully thought about their expectations, and do they take their expectations into account when they construct their bids? To gain a first impression figure 1 shows some examples for bids and expectations from

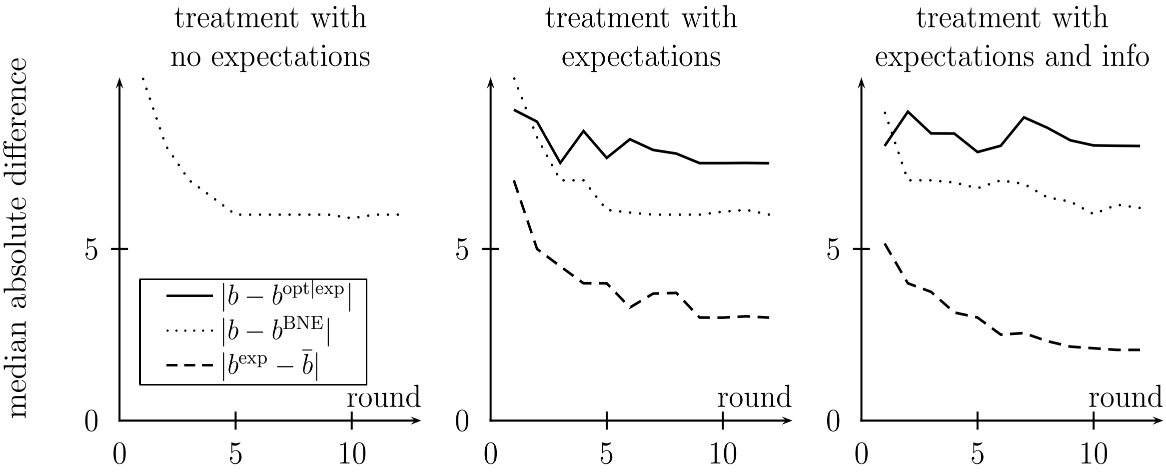


FIGURE 6: Convergence of bids and expectations

the experiment. In section 4.1 we will check convergence of behaviour. Section 4.2 looks at treatment effects. In section 4.3 we see whether participants in the experiments form reasonable expectations and section 4.4 will check whether bids follow actually best replies to these expectations. Only after all these checks have been done we will present results in section 5.

4.1 Convergence

Our experiment lasts for 12 rounds. In figure 6 we look at convergence of bids and expectations for the three different treatments.

Theorists might be tempted to describe players' bids b as Bayesian Nash equilibrium bids b^{BNE}. Then the absolute difference $|b - b^{\text{BNE}}|$ should be zero. The dotted line in figure 6 shows the median of $|b - b^{\text{BNE}}|$ over time. While the distance between experimental bids and equilibrium decreases during the first three or four rounds of the experiment it does not change very much during the second half of the experiment and remains at a high level. This is consistent with the persistent deviation from equilibrium bids which has been observed in many previous experiments.

Another ingredient of players' behaviour is formation of expectations. Are expectations correct? If they are not correct, are they increasing in precision? A payoff maximising player in our experiment who knows the true distribution function of all bidding functions will report the median bidding function as the expected bid. In figure 6 we compare the median bid $\bar{b}$ with the expectation b^{exp}. The dashed line shows the median of $|b^{\text{exp}} - \bar{b}|$. If expectations were perfect then this difference should be zero. Again, the difference decrease during the first few

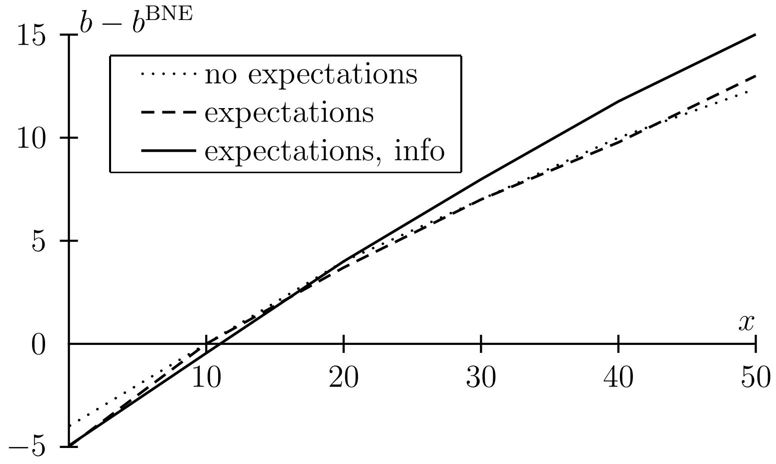


FIGURE 7: Median overbidding

rounds of the experiment and becomes more stable towards the end.

Based on bidders' expectations b^{exp} we can for each bidder and each period determine a best reply bid $b^{\text{opt}|\text{exp}}$ (examples are shown in figure 1). With players who always choose a bid b which is a best reply $b^{\text{opt}|\text{exp}}$ given their expectations the difference $|b - b^{\text{opt}|\text{exp}}|$ should be zero. The solid line in figure 6 shows the median of $|b - b^{\text{opt}|\text{exp}}|$. Also this difference remains stable during the second half of the experiment.

We will discuss expectations b^{exp} and bids b below in more detail. The purpose of this section is to show convergence of our results. In the following we will restrict our analysis to the second half of the experiment where behaviour is fairly stable. However, all main results do not change if all periods of the experiment are included.

4.2 Treatment effects

Does the method we are introducing to measure behaviour actually change behaviour? Figure 7 compares median overbidding under the three different treatments. In equilibrium there would be no overbidding at all, i.e. we should observe a horizontal line. The increasing lines for the three treatments show that there is overbidding for large valuations in all treatments. We see that overbidding is, if at all, even more pronounced under the expectation with info treatment. To test this formally we look at the difference between actual bids $b(x)$ under the expectation treatments and the median bids $\bar{b}^{\text{noexp}}(x)$ for different valuations x

expectations; 8 independent obs.					
	β	σ	t	$P_{>t}$	95%conf. interval
x	$-.0016$	.02209	-0.072	0.944	$-.05384, .05064$
β_0	$-.8499$	.87882	-0.967	0.366	$-2.928, 1.2282$
expectations, info; 11 independent obs.					
	β	σ	t	$P_{>t}$	95%conf. interval
x	.04762	.02164	2.200	0.052	$-.00061, .09584$
β_0	-1.7251	.39805	-4.334	0.001	$-2.612, -.83819$

TABLE 2: Estimation of equation (2) for the two expectation treatments

in the no expectation treatments.[1] If introducing expectations in the experiment does not affect bids these differences should be zero. We estimate the following equation:

$$b(x) - \bar{b}^{\text{noexp}}(x) = \beta_x x + \beta_0 \tag{2}$$

Estimation results are given in table 2.[2] We see that introducing expectations without information about the bidding function of the opponent does not have a significant impact. Introducing expectations with information about the opponent's bidding function significantly increases overbidding for large valuations measured as β_x and also increases underbidding for small valuations (β_0). Thus, at least for the treatment with information we do find an (albeit small) treatment effect. However, the effect does not diminish the deviation from symmetric risk neutral Bayesian Nash equilibria. On the contrary, in this treatment the deviation from equilibria is even stronger.

4.3 Quality of expectations

In our experiment subjects have an incentive to give precise expectations. The larger the deviation of their expectation from their opponent's true bidding function, the smaller is their payoff. Does this, indeed, induce them to make good and precise estimates or did we ask too much of our participants?

[1]We did the same exercise with mean bids to obtain basically the same result. Since medians are less vulnerable to outliers we are concentrating on medians here. The structure of equation (2) does not require overbidding to be linear in x (though it requires the treatment effect to be linear). One can impose such linear relationship between x and the amount of overbidding and obtains very similar results.

[2]When calculating levels of standard deviations and levels of significance we have to take into account that observations within our experimental sessions may be correlated. We can safely assume that covariances of observations from different sessions are zero. Covariances of observations from the same experiment are replaced by the appropriate product of the residuals (Rogers, 1993). We will use this approach throughout the paper to calculate standard errors.

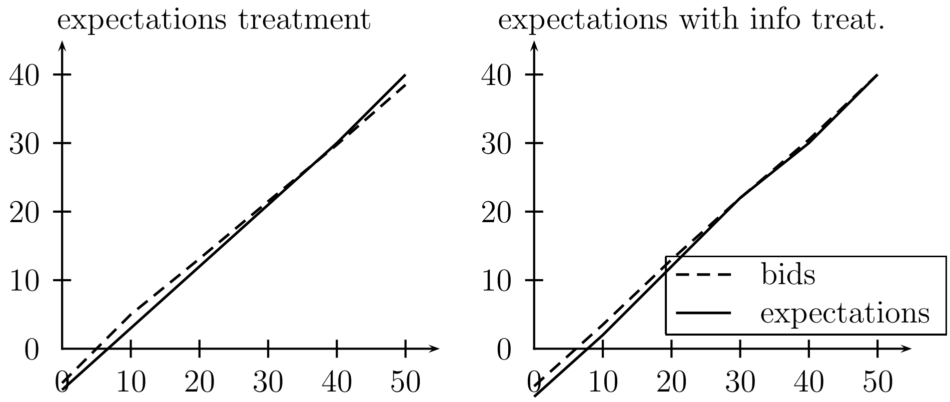


FIGURE 8: Median bids and median expectations

	n	$\beta^1 - 1$	t	$P_{>\|t\|}$	P_{bin}
expectations	8	.0736	2.59	0.036	0.070
expectations, info	11	.0291	2.01	0.072	0.227
all	19	.0478	3.16	0.005	0.019

TABLE 3: Testing $\beta_i^1 - 1 = 0$ for equation (3)

First, the participants themselves seem to be quite satisfied with their job. At the end of the experiment participants report whether they find the experiment complicated on a scale from 1 (not complicated) to 5 (very complicated). Participants in the expectation treatments rank the experiment with an average of 1.8 as slightly more complicated as those in the no expectation treatments who give an average of 1.51. Nevertheless, 1.8 still looks like a confident participant.

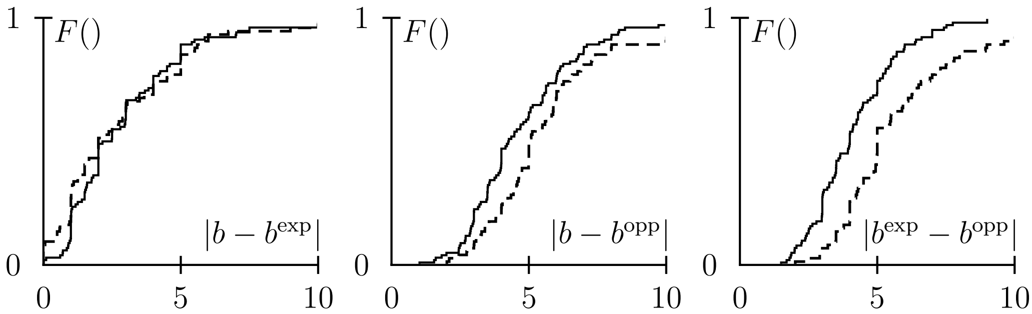
Let us next test whether expectations are objectively good. Then we will see why they are good, i.e. whether they result from mere introspection or whether information about other bidding functions plays a role as well.

Figure 8 shows median bidding functions and medians of expected bids for the two expectation treatments. We see that expectations are, indeed, very close to bids. To check this more formally we determine for each period, treatment, and valuation the median bidding function $\bar{b}_t(x)$. Ideally, this is what participants should expect in each period.[3] For each individual i we estimate now

$$b_i^{\exp}(x) = \beta_i^1 \bar{b}_t(x) + \beta_i^0 + u\,. \tag{3}$$

Table 3 reports a t-tests as well as a binomial test for $\beta_i^1 = 1$. Expected bidding

[3] As above we did the same exercise with mean bids to obtain basically the same result. Since medians are less vulnerable to outliers we are concentrating on medians here.



Medians are taken for each participant separately with the first six periods discarded. The expectation with info treatment is shown as a solid line, the expectation without info treatment is shown as a dashed line.

FIGURE 9: Cumulative distribution of median absolute differences between bids

functions are slightly steeper than actual bidding functions, the difference is also significant, but small.

The estimation of equation (3) can tell us how good expectations are, but it does not reveal the causality between bids and expectations. Do participants really have a good model of the behaviour of the population in mind and use this to form good expectations, or do participants follow a naïve procedure: not knowing at all what they should expect they simply copy their own bid into the expectation graph?

The examples that are given in figure 1 on page 5 suggest that this is not the case. Expectations seem to differ from actual bids. More systematically, in the left part of figure 9 we show cumulative distribution of median absolute differences between own bids and expectations $|b - b^{\text{exp}}|$. Medians are taken for each participant separately with the first six periods discarded. We see that $|b - b^{\text{exp}}|$ is positive for almost all participants, i.e. participants choose a bid which differs from what they expect their opponent to do. The differences between own and opponent's true bids $|b - b^{\text{opp}}|$ and own expectations and opponent's true bids $|b^{\text{exp}} - b^{\text{opp}}|$ are included in the figure as a reference.

To further investigate the question whether participants form valid expectations one might suggest to regress individual expectations on individual bids. This can be a difficult exercise since expectations already causally affect bids and disentangling the two directions of causality is hard. As an alternative and, perhaps, simpler approach we use the data from our 'expectation with info' treatment. Since bidders are matched in every period with a new random opponent the bidding function of the opponent in the current round is not a perfect predictor for the opponent in the next round. Nevertheless, it provides some new information

	n	β	t	$P_{>\|t\|}$	P_{bin}
	11	.0373	2.916	0.015	0.065

TABLE 4: Test for the coefficient of $\Delta_{t-1}b_j$ in equation (4)

	β	σ	t	$P_{>t}$	95%conf. interval
$\Delta_{t-1}b_j$	.02566	.00826	3.106	0.011	.00725, .04406
$\Delta_t b_i$	.4922	.15471	3.181	0.010	.14749, .83692
β_0	.23205	.04485	5.174	0.000	.13211, .33198
independent obs.	11				

TABLE 5: Estimation of equation (5)

about the distribution of bidding functions in the population. We use the opponent's bid in this treatment as an explanatory variable for expectations and estimate the following equation in first differences[4]:

$$\Delta_t\, b_i^{\text{exp}} = \beta_j \cdot \Delta_{t-1}b_j + \beta_0 + u \tag{4}$$

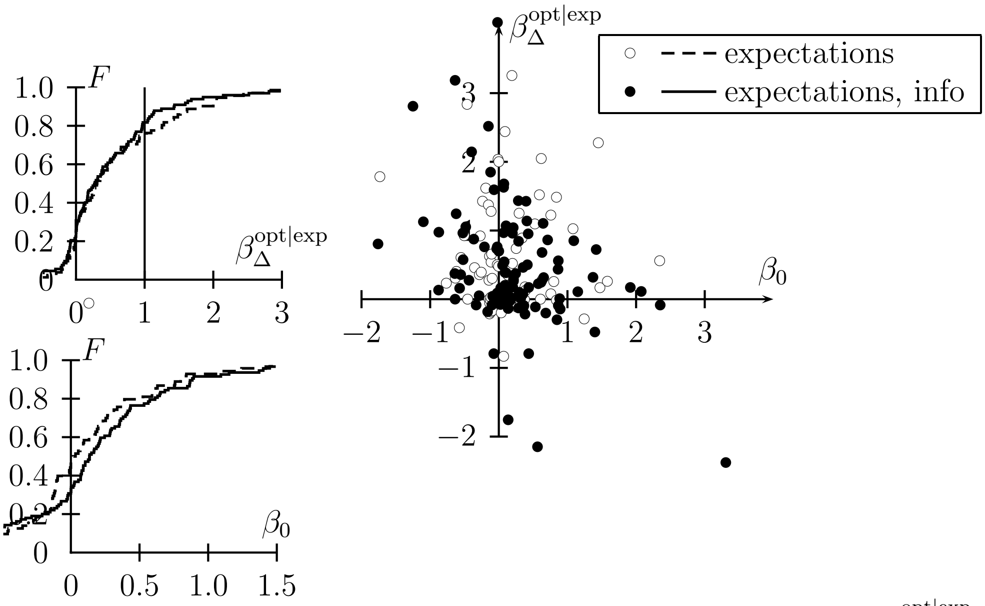
How large the coefficient β in equation (4) should be depends on the prior expectations of the bidder. A bidder with no prior expectations should have a β close to one. A bidder with strong prior expectations who is convinced that nothing new can be learned from the current opponent should have a $\beta = 0$. The result of estimating the coefficient β is shown in table 4. We see that the coefficient of $\Delta_{t-1}b_j$ is positive and significantly different from zero. Thus, changes in an opponent's individual bidding function seem to have an effect on a bidder's expectations for the next period.

Could it be that a positive coefficient of $\Delta_{t-1}b_j$ in equation (4) arises due to an indirect effect? Naïve bidders see opponents' bids rise, in response they increase their own bids (without thinking about expectations), and, when asked about expectations, they simply use their own bids as expectations. To test this, we add $\Delta_t b_i$ as an explanatory variable in equation (5).

$$\Delta_t\, b_i^{\text{exp}} = \beta_j \cdot \Delta_{t-1}b_j + \beta_i \cdot \Delta_t b_i + \beta_0 + u \tag{5}$$

Table 5 reports estimation results. We see that, even if we allow bidders to follow the above naïve strategy, the coefficient of $\Delta_{t-1}b_j$ is still significantly positive, i.e. bids of opponents do directly affect expectations. A positive and significant

[4]Since b_i^{exp} and b_j are likely to be correlated we can not use absolute values.



The two diagrams on the left show the cumulative distribution for the estimation of $\beta_\Delta^{\mathrm{opt|exp}}$ and β_0 of each player. The diagram on the right shows the joint distribution with one dot for each player.

FIGURE 10: Estimation of equation (6)

coefficient for $\Delta_t b_i$ is no confirmation of the above naïve model. Also with rational players there should be a relationship between b and b^{exp}.

To summarise: We find that bidders in the experiment make expectations which are close to actual bids. Furthermore, bidders seem to use available information to form expectations in a sensible way.

4.4 Quality of reactions to expectations

Whatever the expectations are, can we assume that bidders make optimal bids given their expectations? To answer this question we construct for each bidder and each period the best reply given this bidder's expectations $b^{\mathrm{exp}}(x)$. We call this best reply $b^{\mathrm{opt|exp}}(x)$. Since we have to derive this best reply under the constraint that bids are stepwise linear with support points $\{0, 10, 20, 30, 40, 50\}$ we use a numerical procedure to find $b^{\mathrm{opt|exp}}(x)$. Some examples are shown in figure 1 on page 5. We then compare actual bids b with best replies $b^{\mathrm{opt|exp}}$ and estimate

$$\Delta b_i(x) = \beta_\Delta^{\mathrm{opt|exp}} \cdot \Delta b^{\mathrm{opt|exp}} + \beta_0 + u\,. \tag{6}$$

A rational bidder should have $\beta_\Delta^{\mathrm{opt|exp}} = 1$. A bidder who is slow in adapting and who also takes past experience into account should have $\beta_\Delta^{\mathrm{opt|exp}} < 1$. Results of estimating equation (6) for each bidder individually are shown in figure 10. A formal test is given in table 6. The coefficient $\beta_\Delta^{\text{opt}|\text{exp}}$ is significantly positive,

	n	$\beta_\Delta^{\text{opt}|\text{exp}}$	t	$P_{>|t|}$	P_{bin}
info	8	.5698	5.373	0.001	0.008
info, exp.	11	.4357	4.243	0.002	0.001
all	19	.4921	6.599	0.000	0.000

TABLE 6: Test of $\beta_\Delta^{\text{opt}|\text{exp}} = 0$ from equation (6)

i.e. bidders indeed take the best reply $b^{\text{opt}|\text{exp}}$ into account when choosing their bid b.

5 Results

In the previous section we have tested the reliability of our experimental framework. In this context we have in equations (4) and (5) studied how actual bids affect expectations. In equation (6) we looked at how expectations affect actual bids.

In this section we want to compare bids and expectations more closely with Bayesian Nash equilibrium. Thus, the explanatory variable in our regression is no longer the actual bid b or the actual expectation b^{exp}, as it was in the previous section, but rather what they should do if they followed equilibrium bidding functions and best replies, i.e. b^{BNE} and $b^{\text{opt}|\text{exp}}$. As already stated above, we do not aim at providing a complete and correct description of the thought process of real individuals. We are restricting ourselves to the structure of Bayesian Nash equilibrium derivation. In a first step we want to explore what happens on the way from $b^{\text{BNE}}(x)$ to $b^{\text{opt}|\text{exp}}$. In a second step we want to understand how $b^{\text{opt}|\text{exp}}$ translates into b. We want to measure whether deviations between actual and equilibrium bids are rather due to non equilibrium expectations or whether they are due to wrong best replies. We estimate the following two equations:

$$b_i^{\text{opt}|\text{exp}}(x) = \beta^{\text{BNE}} \cdot b^{\text{BNE}}(x) + \beta_0^{\text{BNE}} + u \qquad (7)$$

$$b_i(x) = \beta^{\text{opt}|\text{exp}} \cdot b_i^{\text{opt}|\text{exp}}(x) + \beta_0^{\text{opt}|\text{exp}} + u \qquad (8)$$

In equation (7) we regress the best reply bid $b^{\text{opt}|\text{exp}}(x)$ on the Bayesian Nash equilibrium bid $b^{\text{BNE}}(x)$. We regress on $b^{\text{BNE}}(x)$ since our reference point is the Bayesian Nash equilibrium. If participants expect that the others use equilibrium

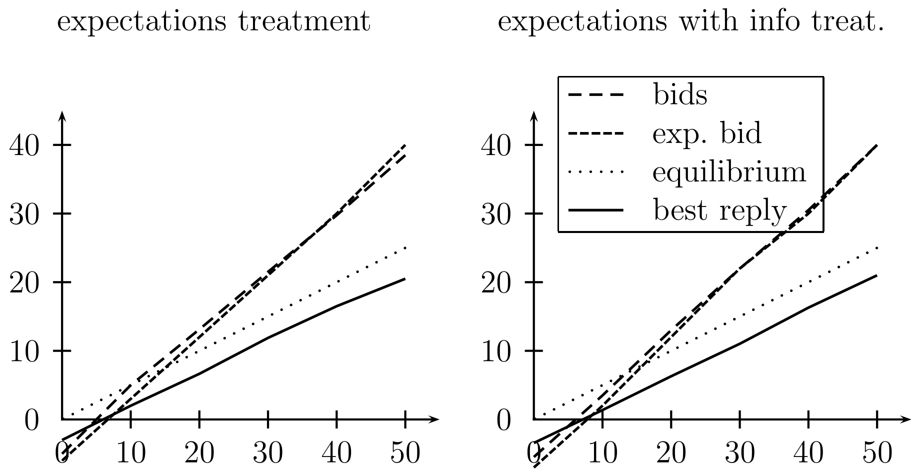
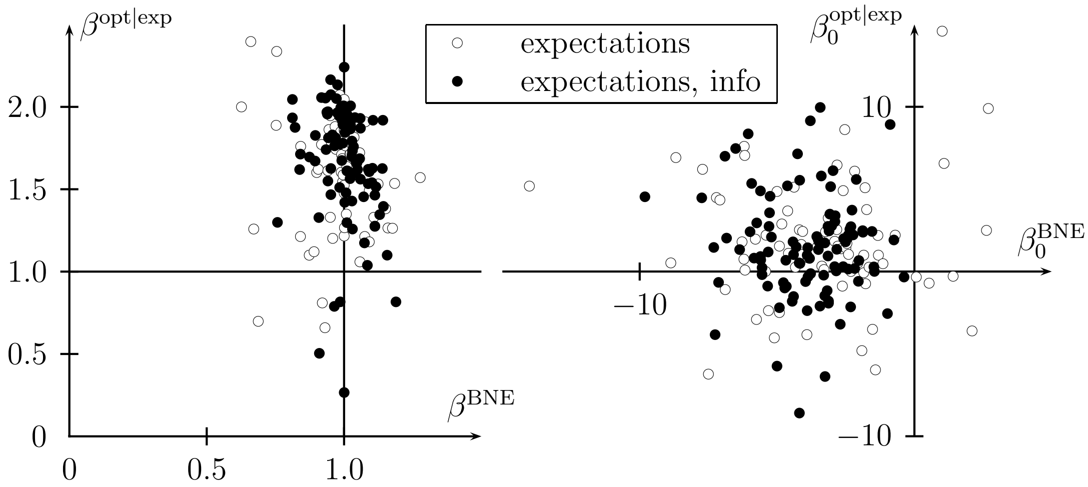


FIGURE 11: Median bids and median best replies



The coefficients of the linear terms are shown on the left, those of the constants are on the rights.

FIGURE 12: Estimating equations (7) and (8).

bids, then the coefficient β^{BNE} should be one. The more a player's expectations deviate from equilibrium bids, the more β^{BNE} will be different from one.

In equation (8) we regress the actual bid $b_i(x)$ on the best reply bid $b^{\mathrm{opt|exp}}(x)$. If a player chooses always the best reply given the expected opponent's bid then $\beta^{\mathrm{opt|exp}}$ should be one. The more a player's actual bid deviates from the best reply bid, the more $\beta^{\mathrm{opt|exp}}$ will be different from one.

Figure 12 and 13 show the distribution of the estimated coefficients. Let us start with equation (7), the relation between expectations and equilibrium bids. In the bottom part of figure 13 we see that β^{BNE} is closely centred around one,

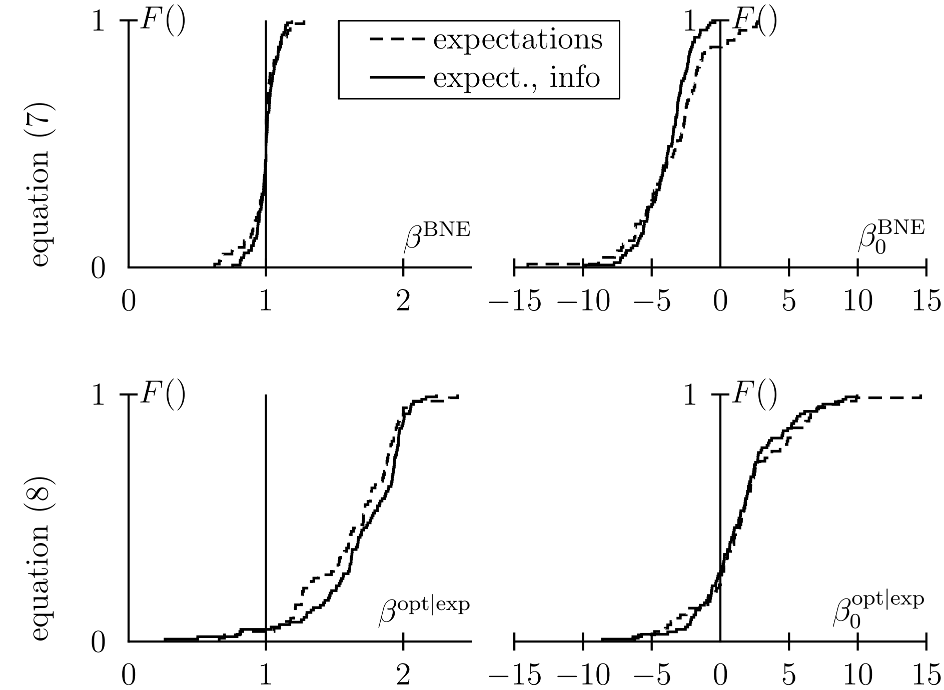


FIGURE 13: Cumulative distribution of coefficients from equation (7) and (8).

though the constant β_0^{BNE} is smaller than zero. What we estimate for β^{BNE} and β_0^{BNE} is also reflected in the median best replies in figure 11: The solid line, which shows the median of the best replies, is almost parallel to the equilibrium bid (dotted line), but slightly below. In other words: Bidders do seem to deviate in their expectations consistently from equilibrium bids. However, the deviation we find would rather explain underbidding, not overbidding. How can it be, then, that most experimental bids are over, and not under the equilibrium bids?

How overbidding enters becomes clear when we look at the estimation results for equation (8). The upper part of figure 13 shows the cumulative distribution of $\beta^{\text{opt}|\text{exp}}$. We see that $\beta^{\text{opt}|\text{exp}}$ is larger than one for most bidders. The constant $\beta_0^{\text{opt}|\text{exp}}$ is close to zero. Tests are reported in table 7.

Let us summarise: We find that there are two effects which determine bidding behaviour. The way bidders form expectations would rather lead to underbidding. The way bidders attempt to optimise against their expectations leads to overbidding. Since the second effect is stronger than the first we observe that in the end most bids are larger than equilibrium bids.

	n	$\beta^{\text{BNE}} - 1$	t	$P_{>\|t\|}$	P_{bin}
expectations	8	-.0167	-1.254	0.250	0.727
expectations, info	11	.0021	0.201	0.844	0.549
all	19	-.0058	-0.694	0.497	0.359
	n	$\beta^{\text{opt}\|\text{exp}} - 1$	t	$P_{>\|t\|}$	P_{bin}
expectations	8	.6297	14.400	0.000	0.008
expectations, info	11	.6943	13.833	0.000	0.001
all	19	.6671	19.569	0.000	0.000

TABLE 7: Testing $\beta^{\text{BNE}} = 1$ for equation (7) and $\beta^{\text{opt}|\text{exp}} = 1$ for equation (8)

6 Concluding remarks

In this paper we investigate if systematic deviations from equilibrium bidding behaviour are due to wrong expectations, or due to wrong best replies against these expectations.

Given the novelty of the approach we have checked carefully the internal validity of our setup. We have found that the expectations we measure are reliable, and that expectations also react to information in a reasonable way.

The main result was presented in section 5: Bidders make systematic mistakes in forming their expectations and in determining their strategy. We found that most of the deviations from equilibrium bids are not related to wrong expectations but to deviations from the best reply against these expectations.

Our results for first-price auctions complement, thus, the findings of Costa-Gomes and Weizsäcker (2004) for 3×3 games: In both situations expectations resemble actual strategies fairly well. In both situations, however, strategies are not best replies to expectations.

Our results also support the standard approach to explain deviations from risk neutral Bayesian Nash equilibrium bids. Risk aversion, regret (see Filiz-Ozbay and Ozbay, 2007), and spite (Morgan, Steiglitz, and Reis, 2003) are explanations that base on correct expectations. We can show that, indeed, the major part of the deviation from standard equilibrium is not due to wrong expectations but happens on the reply side.

We did not find strong support for a model of level k thinking (Crawford and Iriberri, 2007). First, casual inspection of the bidding functions reveals that these are not linear, which they should be if they are derived through a level k thinking process. Second and more importantly, level k bids do not fit level k expectations for any level of k.

When we observe accurate expectations and inaccurate best replies in the lab we should keep in mind that forming precise expectations about opponents' bids might be easier in the lab than in real world auctions. Still, if the difference between bids and best replies is large in the lab we should expect this difference to be significant in the field as well. Many electronic marketplaces assist bidders in forming their expectations by providing detailed data about past and current bids. Given the evidence from our experiment it might be a desirable feature of future marketplaces to assist bidders in determining their best replies.

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A List of independent observations

date	treatment	place	min.bid	participants
20040517-12:21-0	no expectations	Mannheim	-50	8
20040517-12:21-1	no expectations	Mannheim	-50	6
20040517-17:17-0	no expectations	Mannheim	-50	8
20040517-17:17-1	no expectations	Mannheim	-50	8
20031211-18:23-0	no expectations	Mannheim	0	14
20031212-10:45-0	no expectations	Mannheim	0	14
20040519-15:53-0	no expectations	Mannheim	0	8
20040519-15:53-1	no expectations	Mannheim	0	10
20050414-08:55-0	no expectations	Magdeburg	0	10
20050414-08:55-1	no expectations	Magdeburg	0	10
20050414-13:17-0	no expectations	Magdeburg	0	10
20050414-13:17-1	no expectations	Magdeburg	0	10
20050613-08:39-0	no expectations	Magdeburg	0	10
20050613-08:39-1	no expectations	Magdeburg	0	8
20050613-10:27-0	no expectations	Magdeburg	0	10
20050613-10:27-1	no expectations	Magdeburg	0	8
20050613-14:39-0	no expectations	Magdeburg	0	10
20050613-14:39-1	no expectations	Magdeburg	0	8
20050614-08:45-0	no expectations	Magdeburg	0	8
20050614-08:45-1	no expectations	Magdeburg	0	8

continued on next page

date	treatment	place	min.bid	participants
20050614-10:41-0	no expectations	Magdeburg	0	10
20050614-10:41-1	no expectations	Magdeburg	0	8
20050614-14:41-0	no expectations	Magdeburg	0	10
20050614-14:41-1	no expectations	Magdeburg	0	10
20050615-08:49-0	no expectations	Magdeburg	0	10
20050615-08:49-1	no expectations	Magdeburg	0	8
20050615-10:41-0	no expectations	Magdeburg	0	10
20050615-10:41-1	no expectations	Magdeburg	0	8
20050615-14:45-0	no expectations	Magdeburg	0	8
20050615-14:45-1	no expectations	Magdeburg	0	8
20050616-08:53-0	no expectations	Magdeburg	0	10
20050616-08:53-1	no expectations	Magdeburg	0	8
20050616-10:17-0	no expectations	Magdeburg	0	8
20050616-10:17-1	no expectations	Magdeburg	0	8
20050616-14:39-0	no expectations	Magdeburg	0	10
20050616-14:39-1	no expectations	Magdeburg	0	10
20050207-10:53-0	expectations w. info	Mannheim	-50	8
20050209-14:09-0	expectations w. info	Mannheim	-50	12
20050209-16:11-0	expectations w. info	Mannheim	-50	6
20050414-10:37-0	expectations w. info	Magdeburg	-50	10
20050414-10:37-1	expectations w. info	Magdeburg	-50	10
20050414-16:35-0	expectations w. info	Magdeburg	-50	10
20050414-16:35-1	expectations w. info	Magdeburg	-50	10
20050415-08:59-0	expectations w. info	Magdeburg	-50	8
20050415-08:59-1	expectations w. info	Magdeburg	-50	8
20050415-11:11-0	expectations w. info	Magdeburg	-50	10
20050415-11:11-1	expectations w. info	Magdeburg	-50	10
20050511-10:51-0	expectations	Magdeburg	-50	10
20050511-10:51-1	expectations	Magdeburg	-50	10
20050511-14:55-0	expectations	Magdeburg	-50	10
20050511-14:55-1	expectations	Magdeburg	-50	10
20050512-09:01-0	expectations	Magdeburg	-50	10
20050512-09:01-1	expectations	Magdeburg	-50	8
20050512-12:59-0	expectations	Magdeburg	-50	8
20050512-12:59-1	expectations	Magdeburg	-50	8

B Conducting the experiment

Participants were recruited by email and could register for the experiment on the internet.

- At the beginning of the experiment participants drew balls from an urn to determine their allocation to seats in the laboratory.
- Then participants took a simple language test (participants had to find

the correct word or form to complete a sentence). Those who failed the language test on at least two items out of ten could not participate (this did not happen very often since participants knew about the language test when they booked the experiment).

- The remaining participants obtained written instructions in German (see section B.1). These instructions vary slightly depending on the treatment. In the following we give a translation of the instructions.
- After answering control questions on the screen (see section B.2) subjects entered the treatment. After completing the treatment they answered a short questionnaire on the screen and were paid in cash. The experiment was done with z-Tree Version 3β Fischbacher (2007).

B.1 Instructions

General information

You are participating in a scientific experiment that is sponsored by the Deutsche Forschungsgemeinschaft (German Research Foundation). If you read the following instructions carefully then you can—depending on your decision—gain a considerable amount of money. It is, hence, very important that you read the instructions carefully.

The instructions that you have received are only for your private information. **During the experiment no communication is permitted.** Whenever you have questions, please raise your hand. We will then answer your question at your seat. Not following this rule leads to exclusion from the experiment and all payments.

During the experiment we are not talking about Euro, but about ECU (Experimental Currency Unit). Your entire income will first be determined in ECU. The total amount of ECU that you have obtained during the experiment will be converted into Euro at the end and paid to you in **cash**. The conversion rate will be shown on your screen at the beginning of the experiment.

Information regarding the experiment

Today you are participating in an experiment on auctions. The experiment is divided into separate rounds. We will conduct **12 rounds**. In the following we explain what happens in each round.

In each round you bid for an object that is being auctioned. Together with you another participant is also bidding for the same object. Hence, in each round, there are **two bidders**. In each round you will be allocated randomly to another participant for the auction. **Your co-bidder in the auction changes in every round.** The bidder with the highest bid has obtained the object. If bids are the same the object will be allocated randomly.

For the auctioned object you have a valuation in ECU. This valuation lies between 50 and 100 ECU and is determined randomly in each round. **From this range you will obtain in each round new and random valuations for the object.** The other bidder in the auction also has a valuation for the object. The valuation that the other bidder attributes to the object is determined by the same rules as your valuation and changes in each round, too. All possible valuations of the other bidder are also in the interval from 50 to 100 from which also your valuations are drawn. All valuations between 50 and 100 are equally probable. Your valuations and those of the other player are determined independently. You will be told your valuation in each round. **You will not know the valuation of the other bidder.**

Experimental procedure

The experimental procedure is the same in each round and will be described in the following. Each round in the experiment has two stages.

1st Stage

In the first stage of the experiment you see the following screen *[[here the instructions show a screen similar to figure 2 or figure 3. Other than the figure the screenshots in the instructions did not provide an example bidding function.]]*

At that stage **you do not know your own valuation for the object in this round.** On the left side[5] of the screen you are asked to enter a bid for **six hypothetical valuations** that you might have for the object. These six hypothetical valuations are 50, 60, 70, 80, 90, and 100 ECU. Your input into this table will be shown in the graph on the left side of the screen when you click on "draw bids". In the graph the hypothetical valuations are shown on the horizontal axis, the bids are shown on the vertical axis. Your input in the table is shown as six points in the diagram. **Neighbouring points are connected with a line automatically.** These lines determine your bids for all valuations **between** the six valuations for which you have entered a bid.

[[the following paragraph is only shown in the treatments with expectations: On the right side you are asked to enter **your expectations regarding the bids of the other bidder**. Please enter again for six hypothetical valuations **your**

[5] In the no expectation treatment this was the right side.

expectation of the bid of the other bidder. If your expectation regarding the bids of the other bidder deviates from the actual bids of the other bidder then an amount which depends on the size of the deviation will be subtracted from your account.*]]*

The screen of the other bidder looks identical. He also enters bids for six hypothetical valuations *[[the following only in treatments with expectations:* and expectations regarding your bids*]]*. You and the other bidder can not see your mutual bids and expectations.

2nd Stage

The actual auction takes place in the second stage of each round. In each round we will play not only a single auction but **five auctions**. This is done as follows: **Five times a random valuation is determined** that you have for the object. Similarly for the other bidder five random valuations are determined. You see the following screen:

[[here the instructions show a screen similar to figure 4. Other than these figures the screenshots in the instructions do not provide example bidding functions, bids, valuations, and payoffs.]]

For each of your five valuations the computer determines your bid according to the graph from stage 1. If a valuation is precisely 50, 60, 70, 80, 90, or 100 then the computer takes the bid that you gave for this valuation. If a valuation is between these points then your bid is determined according to the connecting line. In the same way the bids of the other bidder are determined for his five valuations. Your bid is compared with the one of the other bidder. The bidder with the higher bid has obtained the object.

Your income from the auction:

For each of the five auctions the following holds:

- The bidder with the higher bid gets the valuation he had for the object in this auction added to his account minus his bid for the object.
- The bidder with the smaller bid gets **no income** from this auction.

[[[the next two paragraphs and the screenshot are only shown in the treatments with expectations:

The possible reduction if expectations are not correct The following screen again shows the expectations you entered in the first stage:

[[here the instructions show a screen similar to figure 4 or 5. Other than these figures the screenshots in the instructions do not provide examples for expected bidding functions, no examples for income and no examples for a loss.]]

The average difference between your expectations and the actual bids of the other bidder for the six hypothetical valuations 50, 60, 70, 80, and 100, multiplied with the conversion factor that is shown on the screen, is subtracted from your account.*]]]*

You total income in a round is the sum of the ECU income from those auctions in this round *[[the following part is only shown in the treatments with expectations:* **minus the reduction for your incorrect expectations regarding the other bidder.***]]*

This ends one round of the experiment and you see in the next round again the input screen from stage 1.

At the end of the experiment your total ECU income from all rounds will be converted into Euro and paid to you in cash together with your Show-Up Fee of 3.00 Euro.

Please raise your hand if you have questions.

B.2 Control questions

After participants had read the instructions they were asked to answer control questions. These questions were implemented with z-Tree. Questions were presented and answered sequentially. When a question was answered correctly, participants saw the text "This answer is correct" (in German). Otherwise participants saw the text "This answer is not correct". In this case they got a brief explanation how to derive the correct answer for this question.

The structure of this treatment was (translated into English) as follows:

- The following control questions are supposed to improve your understanding of the experiment. We use some arbitrarily chosen examples to make you familiar with the calculation of profits and other rules in the auction.

  Please answer the following questions. You can check yourselves whether your answers are correct. The actual experiment will start after the last question.

- Please note: When you enter numbers with a decimal fraction you have to use the decimal point as a separator, not the decimal comma.
- If you need a calculator, please click on the symbol on your screen.

1. Assume your valuation is 63.25 ECU and your bid that is derived from the bid function in the graph is 40 ECU. What is your income in this auction if
   (a) the other bidder bids less than your bid?
   (b) the other bidder bids more than your bid?
2. Assume your valuation is 50 ECU and your bid that is derived from the bid function in the graph is 60 ECU. What is your income in this auction if
   (a) the other bidder bids less than your bid?
   (b) the other bidder bids more than your bid?
3. Assume your valuation in this auction is 76.20 ECU. What is your valuation in the next auction?
   - 76.20 ECU / one can not say / 0 ECU
4. Assume your valuation in this auction is 51.67 ECU. What is the valuation of the other bidder in this auction?
   - one can not say / 51.67 ECU / 100 ECU
5. The following table shows an example for your expectations regarding the bids of the other bidder as well as the actual bids of the other bidder.

value	expected bid	actual bid
50	40	40
60	40	40
70	40	30
80	40	40
90	40	50
100	40	50

   What amount will be subtracted from your account due to wrong expectations if the conversion factor is 1?
6. Assume that in one round you have won one auction with a valuation of 80 ECU and a bid of 62 ECU. Furthermore, you lost 7 ECU due to wrong expectations. What is your total income from this round?

B.3 End of the experiment

At the end of the experiment participants completed a questionnaire, again with z-Tree. From their answers we know that about 20% of all participants were female, their median age was 23, about 68% were students of economics and business administration, 73% had participated already in another experiment, and 33% already in another experiment with auctions (Subjects could participate only once in the experiment that we describe in this paper). They found the experiment not very complicated (on a scale from 1 (not complicated) to 5 (very complicated) the average rating was 1.56).

After participants had completed the questionnaire each of them obtained a sealed envelope with their profit from the experiment and left the laboratory.