

## Perfect versus Imperfect Observability—An Experimental Test of Bagwell's Result\*

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THIS PAPER IS DEDICATED TO TOBIAS HÄNDEL, WHO HELPED US IN  
CONDUCTING THE EXPERIMENTS. HE DIED IN APRIL 1998.

In a seminal paper Bagwell ((1995). *Games Econom. Behav.* 8, 271–280) claims that the first mover advantage, i.e., the strategic benefit of committing oneself to an action before others can, vanishes completely if this action is only imperfectly observed by second movers. In our paper we report on an experimental test of this prediction. We implement four versions of a game similar to an example given by Bagwell, each time varying the quality of the signal which informs the second mover. For experienced players we do not find empirical support for Bagwell's result. *Journal of Economic Literature* Classification Numbers: C72, C92. © 2000

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### 1. INTRODUCTION

The existence of a first mover advantage, i.e., of the strategic benefit of committing oneself to an action before others can, is a celebrated insight of game theory. It was first demonstrated by von Stackelberg (1934) in the context of a quantity setting duopoly. Schelling (1960) has deepened our understanding of the first mover advantage in at least two respects. First, he described other settings in which commitment to a certain action is

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beneficial; and second, he pointed out necessary conditions for commitment to be strategically advantageous: commitment has to be irreversible and it has to be reliably communicated to the rival.

In a recent paper Bagwell (1995) shows that the reliability of the communication device is indeed crucial for commitment to be valuable. For that purpose he first considers a two-person simultaneous-move game in which no player has the possibility of committing himself. From this game he then constructs a so-called noisy-leader game in which player 1 chooses an action before player 2 does. However, player 2 only receives a stochastic signal about 1's decision. Bagwell's surprising result is that the set of pure-strategy Nash equilibrium outcomes of the noisy-leader game coincides exactly with the set of pure-strategy Nash equilibrium outcomes of the simultaneous-move game.<sup>1</sup> Thus the result that the first mover can select his favorite outcome (henceforth called the Stackelberg outcome) if his actions are perfectly observable disappears in the presence of noise—the strategic benefit of commitment is lost.<sup>2</sup>

Bagwell (1995) focuses on the pure Nash equilibrium because it has desirable properties in this class of games: it exists in the noisy-leader game whenever it exists in the simultaneous-move game; it is selected if one gives priority to strict equilibria; and it is selected by most evolutionary dynamics, as shown by Oechssler and Schlag (1997).<sup>3</sup> Summarizing his results, he claims that “the first-mover advantage is eliminated when there is even a *slight* amount of noise associated with the observation of the first mover's selection” (p. 271).

This focus on pure strategy equilibria is criticised by van Damme and Hurkens (1997). They argue that “the restriction to pure strategy equilibria is not compelling” (p. 284) and show that under certain regularity assumptions each noisy-leader game has an equilibrium in mixed strategies with an associated outcome that converges to the Stackelberg outcome when the noise goes to zero. (Adopting the terminology of van Damme and Hurkens, we shall refer to this equilibrium in mixed strategies as the “noisy Stackelberg equilibrium.”) Furthermore, they propose a new equilibrium selection theory by combining elements from the theory of Harsanyi and Selten (1988) with elements from the theory of Harsanyi (1995). This approach selects the noisy Stackelberg equilibrium.<sup>4</sup>

<sup>1</sup>This holds whenever the second mover's best-response correspondence is single-valued.

<sup>2</sup>For generalizations or extensions of Bagwell's result see Adolph (1996) or Güth et al. (1998b).

<sup>3</sup>These points have been emphasized by Bagwell in personal communications.

<sup>4</sup>Note, however, that van Damme and Hurkens (1997, Proposition 5) identify one class of games, namely those which are dominance solvable, in which the pure-strategy equilibrium is selected if one requires persistency as a stability requirement.

In this paper we test the behavioral relevance of Bagwell's result experimentally. In particular, we are interested in testing whether his claim that the first-mover advantage is *eliminated* in the presence of noise holds true in a laboratory. Therefore, we construct a simple two-person game similar to the example provided by Bagwell. Relying on a between-subjects design, we study four treatments—one with perfect observability of the leader's action and three with noisy signals. In all treatments we provide sufficient opportunities for learning. What we find rejects Bagwell's claim. Play never converges to the Cournot outcome. Rather, Stackelberg followers adapt to the signals received. Stackelberg leaders, in turn, learn and exploit this.

The remainder of the paper is organized as follows. Section 2 introduces the experimental design and presents a game-theoretic analysis of the implemented games. In Section 3 we describe the experimental methods and procedures. The results of the experiments are presented in Section 4. Finally, we discuss our findings in Section 5.

## 2. EXPERIMENTAL DESIGN AND THEORETICAL PREDICTIONS

We study a two-player game which is very similar to the example provided by Bagwell (1995, p. 272). The first mover (or Stackelberg leader) has a binary choice between  $S$  and  $C$ . Afterward the second mover (or follower) receives a signal about the leader's decision. The signal is either  $s$  or  $c$ . For each signal the follower has two choices called  $S_s$  and  $C_s$  if the signal was  $s$  and  $S_c$  and  $C_c$  if the signal was  $c$ . Figure 1 shows the extensive form game for the case of a perfect signal.<sup>5</sup>

It is worth noting that the payoffs were chosen such that fairness issues cannot play a leading role: there is no path implying equal payoffs, and the two pure equilibrium outcomes are associated with similar degrees of inequality.<sup>6</sup>

We implement four versions of this game, each time varying the quality of signals. In treatment NO NOISE the signal is perfect, i.e.,  $\text{prob}(s | S) = \text{prob}(c | C) = 1$ . In treatment LOW NOISE the according probabilities are 0.99, in treatment MEDIUM NOISE they are 0.9, and in treatment HIGH

<sup>5</sup>The payoffs resemble the payoffs of an asymmetric homogeneous market with quantity competition on which the two firms are restricted to choice sets with two quantities only—one pair of quantities being those of the Cournot equilibrium in the unrestricted game, the other pair of quantities being those of the respective Stackelberg equilibrium.

<sup>6</sup>Note that second movers with a strong aversion against disadvantageous inequality (see, for example, Fehr and Schmidt (1999) or Bolton and Ockenfels (1999) might respond with  $C_s$  when confronted with a first mover taking advantage of his position and playing  $S$ . However, the data do not offer much support for such strong inequality aversion (see Section 4.1).

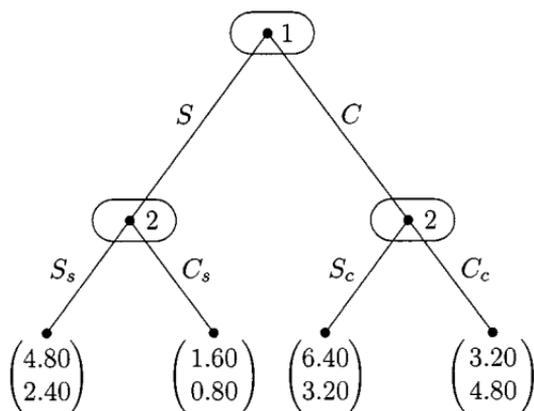


FIG. 1. The game in the case of a perfect signal.

NOISE they are 0.8. The game is played for five or 10 rounds with full anonymity between subjects and a random matching procedure ensuring that no one meets the same opponent twice.

The game with zero noise has two pure equilibria, the Stackelberg equilibrium  $(S, (S_s, C_c))$  and the Cournot equilibrium  $(C, (C_s, C_c))$ . Furthermore, there are two continua of mixed equilibria. Of these equilibria only the Stackelberg equilibrium is subgame perfect and therefore is selected as the solution of the game. The opportunity of moving first exhibits its full advantage: provided players are rational and have mutual knowledge of rationality, the Stackelberg leader can always achieve his preferred equilibrium.

As Bagwell shows, things change dramatically as soon as noise is introduced—even if it is arbitrarily small. If the probability of receiving the correct signal is smaller than 1, only one equilibrium in pure strategies survives, namely the Cournot equilibrium in which the follower simply ignores his signals and the leader chooses  $C$ . The reason for this result is that the follower, if he believes that the leader has taken a certain pure action, can never increase his expected payoff by adapting to the signal. If he believes that the leader has chosen  $S$ , he also prefers playing  $S$ , and if he believes in  $C$ , he prefers playing  $C$ —in both cases regardless of his signal. In other words, adapting to the signal, i.e., playing  $(S_s, C_c)$ , is no longer a dominant strategy for the second mover.

Provided that the noise level is below 25%, the pure Cournot equilibrium is accompanied by two mixed equilibria:

$$\text{prob}(S) = 1 - \varepsilon, \quad \text{prob}(S_s) = 1, \quad \text{and} \quad \text{prob}(S_c) = \frac{1 - 4\varepsilon}{2 - 4\varepsilon} \quad (1)$$

and

$$\text{prob}(S) = \varepsilon, \quad \text{prob}(S_s) = \frac{1}{2 - 4\varepsilon}, \quad \text{and} \quad \text{prob}(S_c) = 0, \quad (2)$$

where  $\varepsilon = \text{prob}(s | C) = \text{prob}(c | S)$ , i.e.,  $\varepsilon$  is the probability of the wrong signal. Note that the mixed strategy equilibrium (1) converges to the Stackelberg and the mixed strategy equilibrium (2) converges to the Cournot outcome as the noise,  $\varepsilon$ , goes to zero. (In the remainder of this paper the mixed equilibrium (2) will be referred to as the noisy Cournot equilibrium.)

In our setup all of these theoretical results hold for all rounds: since interaction is anonymous and one-shot, the five (respectively 10) rounds are repetitions of static games and not a repeated (or dynamic) game giving rise to further equilibria.

Summarizing the theoretical predictions, one should expect

Prediction A: Subjects will play the subgame perfect equilibrium in the treatment without noise.

Prediction B1: Most of the outcomes in treatments with noise will coincide with the Cournot outcome.

Prediction B2: Most of the outcomes in treatments with noise will coincide with the Stackelberg outcome.

Testing prediction B1 is the core issue of the study at hand. If Bagwell's claim that first movers lose their advantage in the presence of noise is of any behavioral relevance, B1 must hold true. As we will see we can find a clear answer to whether B1 holds or not. This is more difficult with respect to prediction B2, which reflects the claim of van Damme and Hurkens. In this regard, we can only offer some first evidence.

### 3. METHOD AND PROCEDURE

The experiments reported in this study were conducted at Humboldt University between January and November 1998. For each of the treatments NO, LOW, and MEDIUM NOISE we conducted a session consisting of five rounds. Forty subjects were allocated to each of these sessions. Furthermore, we ran 10-round sessions for treatments MEDIUM and HIGH NOISE each time with 22 subjects. Thus, altogether 164 subjects participated in the experiment. All subjects in the first three sessions were undergraduates in economics participating in an intermediate micro course. This ensured

some familiarity with the notions of backward induction and Nash equilibrium, which seemed helpful for making a good comparison between the three treatments.<sup>7</sup> The participants of the 10-round session also were undergraduates, although from different courses.

The experiments were run with pen and paper. Subjects were sitting in large lecture rooms with enough space between seats to rule out any attempts at communication. After the subjects received the instructions (see Appendix), questions could be asked and were answered privately. Anonymity was ensured. Roles were assigned randomly. It was announced that there would be five (respectively 10) rounds of the experiment with individual feedback between the rounds, that the matching would be random, but that nobody would meet the same opponent twice.<sup>8</sup> The assigned roles were kept fixed throughout the whole experiment. Sessions lasted between 50 and 75 minutes. Subjects' average total earnings were DM 21.26 in the five-round and DM 46.86 in the 10-round sessions.<sup>9</sup>

The framing of all treatments was identical and as neutral as possible. The game was illustrated by a graph, players were labeled *A* (first mover) and *B* (second mover), and choices were simply labeled *l*(eft) and *r*(ight) for the first and *L* and *R* for the second mover. In treatment NO NOISE first movers received decision sheets in each round, on which they had to note their code numbers and their decisions by entering the appropriate letter in a box. These sheets were then passed on to the followers,<sup>10</sup> who had to insert their code numbers and decisions on the same sheet. Thus, they immediately had full information about what happened in the course of their game. Afterward we collected the sheets again and passed them back to the first movers to inform them about the outcome of the play. Then we collected the sheets again, and the next round was started.

In treatments LOW, MEDIUM, and HIGH NOISE first movers received a small white sticker and an envelope instead of a decision sheet. They had to write down their decision on the sticker. Then they stuck it on the inside of the envelope and wrote their code number on the envelope. After that we proceeded with the chance moves. All subjects carried them out themselves by grabbing numbered chips out of an urn containing 100 chips. Depending on the chosen chip, the experimenters wrote the signals on the envelopes,

<sup>7</sup>At least it ensured maximum homogeneity of the three subgroups facing the different noise levels.

<sup>8</sup>We employed the rotation-matching scheme as introduced by Cooper *et al.* (1996) and thoroughly discussed by Kamecke (1997).

<sup>9</sup>Note that subjects in the treatments with noise received a flat payment of DM 5 in the case of the five-round and DM 10 in the case of the 10-round sessions to compensate them for the longer time they had to spend.

<sup>10</sup>The way in which we allocated the first mover decisions to the followers was not observable.

which were sealed and collected afterward.<sup>11</sup> The sealed envelopes were then handed out to the followers, who had to write code numbers and decisions on them. When all subjects acting as followers had made their decisions, they were allowed to open the envelopes to learn about the actual decisions of their partners. After the envelopes were collected they were passed back to the leaders to inform them about the reaction of the followers. This completed a round.<sup>12</sup>

#### 4. RESULTS

Table I summarizes the results of the five-round treatments; Table II does the same for the 10-round treatments. For each round the tables show the total absolute frequencies of first and second movers' decisions at their respective information sets. In each of these tables the noise levels are shown in the top lines (in parentheses), and the bottom lines show aggregated choices across rounds. In the following section we will first analyze each of the four treatments separately, discussing only some comparisons across them. After that, we will focus on Predictions B1 and B2 by comparing the experimental data with both Bagwell's pure equilibrium prediction and the mixed equilibrium prediction of van Damme and Hurkens.

##### 4.1. *No NOISE*

In treatment *NO NOISE* all first-round decisions are in line with equilibrium play. Seventy five percent of all observations coincide with the subgame perfect Stackelberg outcome, 25% with the Cournot outcome. All followers play best replies. In the second round the number of first movers playing *S* increases by two (three players switched from *C* to *S*, one from *S* to *C*). Of all followers 18 maximized their monetary payoff, while two punished leaders who had gone for their preferred equilibrium.<sup>13</sup> On the

<sup>11</sup>In treatment *LOW NOISE* the second mover got the wrong signal if the chip showed the number 100; otherwise she got the right signal. In treatment *MEDIUM NOISE (HIGH NOISE)* the second mover got the wrong signal if the chip showed the numbers from 91 to 100 (81 to 100); otherwise she got the right signal.

<sup>12</sup>The obvious reason for this sticker-envelope procedure was that we wanted to have one physical device containing all information about a particular play. However, this device had to be constructed in such a way as to ensure that the followers had no chance of inferring the decisions of the leaders by inspecting this device—hence the stickers and the envelope. Note also that the way the noise was introduced assured subjects that the experimenters did not manipulate nature's move.

<sup>13</sup>One of these two followers continued to do this in all following rounds—he was never subsequently matched with a first mover playing *C*.

TABLE I  
Summary of Experimental Results in the Five-Round Sessions<sup>a</sup>

Round	NO NOISE				LOW NOISE (1%)				MEDIUM NOISE (10%)			
	S		C		S		C		S		C	
	S <sub>s</sub>	C <sub>s</sub>	S <sub>c</sub>	C <sub>c</sub>	S <sub>s</sub>	C <sub>s</sub>	S <sub>c</sub>	C <sub>c</sub>	S <sub>s</sub>	C <sub>s</sub>	S <sub>c</sub>	C <sub>c</sub>
1st	15		5		13		7		7		13	
	15	—	—	5	12	1	1	6	6	1	3	10
2nd	17		3		16		4		10		10	
	15	2	—	3	15	1	1	3	10	—	1	9
3rd	17		3		18		2		9		11	
	15	2	—	3	16	2	—	2	10	1	2	7
4th	14		6		17		3		11		9	
	12	2	1	5	13	3	2	2	11	—	1	8
5th	14		6		19		1		14		6	
	12	2	—	6	18	1	—	1	12	1	—	7
Aggr.	77		23		83		17		51		49	
Choices	69	8	1	22	74	8	4	14	49	3	7	41

<sup>a</sup>In round 4 of session LOW NOISE one S-decision led to a c-signal. In round 2 of MEDIUM NOISE one S and one C produced the opposite signals, in round 3 two C's led to s's, and in round 5 one S led to c.

aggregate level third-round behavior is the same as in round 2. However, the 17 first movers playing according to the subgame perfect solution in round 3 were not identical with the 17 of round 2. What started to happen in round 3 of this session was that subjects got bored. From observing participants during the experiment it seems fair to say that they perfectly understood the situation after the second round and that they could not understand why they were forced to repeat a situation as simple as the one at hand for three further rounds. As only three out of 23 switches from S to C can be explained by the experience of punishment (C<sub>s</sub>), it seems that some subjects started to do something different from before for the pure sake of doing it. This also explains the decreasing number of first movers choosing S after the third round.<sup>14</sup> Having some change seemed worth the sacrifice of money.

<sup>14</sup>An alternative explanation for Stackelberg leaders switching from S to C could be that they followed some general fairness concern, trying to balance their own payoff with the average payoff of their opponents.

In all, we see only weak support for prediction A. Subgame perfect play surely has appeal to the subjects, but another motivational force, whether it is boredom or a vague concern for fairness, sometimes leads them to deviate from perfect play as the game is repeated often.

#### 4.2. *LOW NOISE*

Switching from NO NOISE to LOW NOISE, we see that the introduction of 1% noise does not have a significant influence on first-round behavior. But while there is no convergence of behavior in treatment NO NOISE (and no convergence to expect if the number of rounds would be increased), behavior in treatment LOW NOISE exhibits not only a clear trend but nearly perfect convergence to uniform behavior.<sup>15</sup> However, in contrast to Bagwell's theoretical prediction, play in treatment LOW NOISE does not converge to the Cournot equilibrium but rather to Stackelberg behavior. So the main difference between NO NOISE and LOW NOISE is that the introduction of noise keeps subjects more interested: first movers do not get bored by exploiting their advantage—even those playing *S* in round one continue to do so in all further rounds. Since the structure of the game is cognitively far more demanding than in the absence of noise, there is ample room for learning and the envelope procedure ensures a certain kind of thrill that keeps subjects attentive; play converges to the Stackelberg outcome.

#### 4.3. *MEDIUM NOISE*

Let us first discuss the session over five rounds. While the introduction of 1% noise changes first-round behavior only slightly, with 10% noise play starts significantly far from where it started in treatment NO NOISE ( $p = 0.01$ ,  $\chi^2 = 6.46$  (with regard to first mover behavior)). In fact, the first-round data suggest that Bagwell's result is of empirical relevance, provided the noise level is clearly perceptible. However, as soon as subjects gain more experience, a markedly different picture emerges: more and more first movers decide to commit themselves to the Stackelberg move *S*.

The behavior in the five-round session of MEDIUM NOISE exhibits a clear tendency toward the Stackelberg outcome,<sup>16</sup> which suggests that—as in treatment LOW NOISE—play would move closer or even converge to the Stackelberg outcome if subjects were given the opportunity to play more rounds. We therefore ran an additional MEDIUM NOISE session, this time

<sup>15</sup>First mover behavior in round 5 of this treatment is significantly different ( $p = 0.07$ ,  $\chi^2 = 3.12$  (McNemar, two-tailed)) from behavior in the first round.

<sup>16</sup>Behavior in the fifth round of treatment HIGH NOISE is significantly different from behavior in the first round of this treatment ( $p = 0.039$ ,  $\chi^2 = 4$  (McNemar, two-tailed)).

TABLE II  
Summary of Experimental Results in the 10-Round Sessions

Round	MEDIUM NOISE (10%)				HIGH NOISE (20%)				Wrong Signals	
	S		C		S		C		MEDIUM NOISE	HIGH NOISE
	$S_s$	$C_s$	$S_c$	$C_c$	$S_s$	$C_s$	$S_c$	$C_c$		
1st	3		8		4		7		3C → s	2S → c 2C → s
	5	1	2	3	3	1	2	5		
2nd	10		1		5		6		1S → c	2S → c 2C → s
	8	1	—	2	5	—	1	5		
3rd	6		5		5		6		1S → c	1S → c 1C → s
	4	1	—	6	5	—	—	6		
4th	7		4		3		8		—	2C → s
	6	1	—	4	5	—	—	6		
5th	9		2		5		6		2S → c	1S → c
	7	—	—	4	4	—	1	6		
6th	8		3		7		4		1S → c	2C → s
	7	—	—	4	8	1	—	2		
7th	8		3		7		4		—	1S → c
	7	1	—	3	6	—	1	4		
8th	9		2		4		7		—	1C → s
	9	—	—	2	4	1	1	5		
9th	9		2		6		5		—	1C → s
	9	—	—	2	7	—	—	4		
10th	9		2		5		6		2S → c	2C → s
	7	—	1	3	3	—	—	8		
Aggr.	78		32		51		59		—	
Choices	69	5	3	33	50	3	6	51	—	

over 10 rounds with 22 subjects. Table II summarizes the results of this session. For each round the table shows the total absolute frequencies of first and second movers' decisions.

Again most of the first movers choose the Cournot move *C* in round one.<sup>17</sup> In the second round the picture changes drastically. Suddenly, all first movers but one choose the Stackelberg action, and about three-quarters of the second movers react by also choosing the Stackelberg strategy. Interestingly, all of the eight first movers who chose action *C* in round 1 switched to action *S* in round 2. This happened although four of the first movers earned the highest possible payoff (6.40 DM) in round 1. However, this is not the end of the learning process. In the third round play moves back into the direction of the Cournot outcome. We tend to explain the high fluctuation in the early stages of the session by the deliberate will of the subjects to experiment with the different strategies to learn more about a game which clearly is not trivial. From the third round on, a process similar to the one in LOW NOISE begins, and from the eighth round on play settles down close to the Stackelberg outcome: only 2 of 11 first movers choose the Cournot action in the last three rounds. It turned out that these *C*-decisions in the last rounds stemmed from the same two subjects.<sup>18</sup> Thus, we observe convergence in two respects: not only aggregated play but also individual play has stabilized at the end of this session.

As one can easily see from inspection of Table II, the main driving force of the convergence to Stackelberg is the behavior of second movers. As opposed to Bagwell's claim, they do not ignore their signals but rather adapt to it as if it were perfect. This is learned and exploited by first movers.

#### 4.4. HIGH NOISE

To determine whether followers would still ignore the signal even if it is very noisy, we ran a treatment with 20% noise. Note that this is the highest "prominent" noise level where the noisy-leader game has all three equilibria.

Table II shows the results. The most obvious result is that followers again (with very few exceptions) adapt to the signal. However, this time we do not observe convergence to Stackelberg, as the first movers seem undecided between *S* and *C*. So, don't they learn what is going on this time? The answer is they probably do learn it. However, if one knows that followers adapt to the signal, the expected payoffs of *S* and *C* are very similar with

<sup>17</sup>Note that first mover behavior in round one of this session is again significantly different from first mover behavior in round one of the No NOISE treatment ( $p = 0.01$ ,  $\chi^2 = 6.46$ ).

<sup>18</sup>With one exception (round two), these two subjects always chose action *C*. These subjects' debriefing revealed that they found the action *C* less risky than action *S*. In particular, by almost always choosing *C* they avoided getting the worst payoff of 1.60 DM.

this noise level (4.16 as opposed to 3.84). Thus, it is not surprising that the leaders seem indifferent, since either they are indifferent, or it may take much more time to learn about such subtle payoff differences.

#### 4.5. *Bagwell's Claim*

With regard to prediction B1 (the hypothesis relying on Bagwell's claim of loss of commitment) we make the following two observations:

1. First-round behavior supports B1, i.e., Bagwell's result seems to be of empirical relevance with regard to inexperienced play in the first round, provided the noise level is clearly perceptible (see Tables I and II).

2. Last-round behavior clearly contradicts the predictions of Bagwell's result: when subjects have enough time to gain experience, we observe in LOW NOISE and MEDIUM NOISE clear convergence to the Stackelberg outcome, while in HIGH NOISE subjects play both Stackelberg and Cournot roughly half of the time.

It is important to observe that both first and second movers violate Bagwell's pure equilibrium prediction. With regard to first mover behavior this is clear to the naked eye. With regard to second movers note that the pure equilibrium predicts that second movers will (learn to) ignore their signal and always to play the action  $C$ . But in all noisy-leader games the action  $C_s$  (after signal  $s$ ) is only chosen in 19 of 264 cases (7.2%). In treatment NO NOISE second movers chose action  $C_s$ —after observing *action S*—in 10.4% of all cases. These figures suggest that it makes no difference to subjects whether they observe the *action S* or the *signal s*, which is learned and exploited by leaders.

*Result 1.* If first movers' actions are only imperfectly observable, the unique equilibrium in pure strategies, i.e., the Cournot equilibrium, does not predict play of experienced subjects. Prediction B1 is falsified.

#### 4.6. *The Claim of van Damme and Hurkens*

Next we focus our attention on the noisy Stackelberg equilibrium (1) that is selected by van Damme and Hurkens (1997). However, testing the relevance of this equilibrium statistically is difficult within our setup, as the number of observations of second movers deciding after the signal  $c$  is usually very low.<sup>19</sup> Therefore, it is indeed impossible to reject the hypothesis

<sup>19</sup>One might object that for this purpose we should have used the so-called strategy method by simultaneously asking all players to decide for *every* possible information set. But first of all, our experiment was mainly designed to test Bagwell's strong pure equilibrium prediction. Second, a recent experimental study by Güth *et al.* (1998a) has cast serious doubt on the validity of results obtained by eliciting choices in a sequential game with the strategy method.

that the data in the last periods of LOW NOISE and MEDIUM NOISE were generated by players adopting the noisy Stackelberg equilibrium. However, a different picture emerges in treatment HIGH NOISE. Here we can reject the hypothesis that leaders play  $S$  with probability  $1 - \varepsilon = 0.8$ . Using a one-sided binomial test on data of the last round gives a significance level of 1.2%. Of course, one could argue that leaders are still learning at this stage. As pointed out earlier, the expected payoff difference between  $S$  and  $C$  is quite low—given the noise level and the behavior of the followers—and it might take subjects a very long time to find that out. With respect to followers the best data set is probably the HIGH NOISE one, as there are more decisions after signal  $c$ . Comparing the frequencies predicted by the noisy Stackelberg equilibrium with those of aggregated play as shown in Table II (1.0 vs. 0.94 for  $S_s$  and 0.17 vs. 0.11 for  $S_c$ ), the theory does remarkably well. However, this observation is not really valid, as there are still too few observations. Hence, it is too early to draw a final conclusion regarding the claim of van Damme and Hurkens, and more testing has to be done. Nevertheless, we are able to state the following

*Result 2.* Prediction B2 cannot be falsified for experienced players as long as the noise level does not exceed 10%. With 20% noise, leaders do not converge to the predicted equilibrium strategy within the given time.

## 5. DISCUSSION

Models in which agents can commit themselves to an action before others do and, therefore, may have a strategic advantage are widespread in economic theory. It was already pointed out by Schelling (1960) that one of the requirements of such commitments to be of any value is that they can be reliably communicated to players who move at later stages in the game. Bagwell (1995) impressively demonstrated how important the reliability of the communication channel is if these games are played by rational players. Concentrating on the use of pure strategies, he showed that the first mover advantage is lost if actions made at the first stage of the game are only imperfectly observed by a player moving at the second stage.

To test the behavioral relevance of this result experimentally we implement four versions of a simple two-person sequential-move game that can be viewed as a mini-Stackelberg game with quantity competition in an asymmetric homogeneous market. These versions varied in the quality of the signal regarding the action taken by the first mover that the second mover received. Given the four treatments our main results are (1) Subjects who act as first movers do not always make use of their power when actions are perfectly observable. (2) When the quality of signals is nearly perfect (99%)

play almost completely converges to the Stackelberg outcome. (3) When the quality of signals is lower (90%) first-round behavior is closer to the Cournot outcome but clearly moves in the direction of the Stackelberg outcome in a five-round session and settles down close to the Stackelberg outcome in another 10-round session. This is driven by the very fact that second movers adapt their behavior to the signal they receive. First movers, in turn, learn or anticipate this and are thus encouraged to commit themselves to the Stackelberg action. This leads us to the final result. (4) When the quality of the signal is even worse (80%) followers still adapt to the signal as if it were perfect, but first movers remain undecided between playing Stackelberg and playing Cournot.

Our main conclusion is that first movers in experimental games do not lose their commitment power in the presence of noise. This finding seems to be related to the observation that the physical timing of decisions may serve as an equilibrium selection device enabling the party who comes first to score best.<sup>20</sup> However, whether first movers really learn to pick the noisy Stackelberg equilibrium needs additional experimental study.

Of course, this is not the only option for future experimental research in this area. In our view it seems very interesting to compare simultaneous games and sequential games with and without noise in settings with larger action spaces, e.g., by relying on standard Cournot (respectively Stackelberg) oligopolies.<sup>21</sup> In our setup first movers gain nearly full commitment power in the presence of noise—after a phase of learning and if the noise level is not exceedingly high. Nevertheless it might well be that when strategy spaces are larger, play converges to outcomes somewhere between the Stackelberg and Cournot predictions. However, that commitment power is totally lost in markets like that seems very unlikely in light of our results.

## APPENDIX: TRANSLATED INSTRUCTIONS

*Welcome to our experiment. Read this sheet carefully. In case of questions, give notice! We will then come to you and answer them privately.*

Welcome to our experiment, in which you can earn some money—depending on your decisions and the ones of randomly chosen other participants. The rules are quite simple. Look at the following decision tree:

<sup>20</sup>For studies dealing with behavioral effects of (game theoretically irrelevant) physical timing see, e.g., Rapoport (1997).

<sup>21</sup>See, for example, Levine and Martinelli (1998), who study the noisy-signal technology in a richer environment theoretically.

[Figure of decision tree, similar to Figure 1, with the exceptions that players are labeled “A” and “B,” resp., and that player 1’s actions are labeled “l” and “r” and player 2’s “L” and “R”.]

First, A decides between “l” and “r.” Then, before making his own choice, B is informed about the decision of A.

[This paragraph only in noise treatments.] This information is only partially reliable. This is because it is determined by chance whether B receives the correct or wrong information. This works as follows: After A has made his decision, we take a random draw out of 100 chips. These chips are numbered from 1 to 100. If A draws one of the first 99 [90 (80)] chips, B will receive the correct information about A’s decision. This means that if A has chosen “l” (respectively “r”), we will tell B that A has chosen “l” (respectively “r”). If A draws the chip with the number 100 [a chip with a number from 91 (81) to 100], B receives an incorrect piece of information. This means that if A has chosen “l” (respectively “r”), we will tell B that A has chosen “r” (respectively “l”). After B has received the information about A’s choice, he has to make his decision. This means that B has to decide between “L” and “R.” The real decision of A (which, as explained above, need not necessarily be identical with the one transmitted to B) and the decision of B determine the payoffs.

There are four possible cases:

A chooses “l,” B chooses “L”: In this case A receives 4.80 DM and B receives 2.40 DM.

A chooses “l,” B chooses “R”: In this case A receives 1.60 DM and B receives 0.80 DM.

A chooses “r,” B chooses “L”: In this case A receives 6.40 DM and B receives 3.20 DM.

A chooses “r,” B chooses “R”: In this case A receives 3.20 DM and B receives 4.80 DM.

[This paragraph only in noise treatments.] The procedure is as follows: A writes his decision whether to choose “l” or “r” on a little sticker. Then he sticks the sticker on the inside of an envelope, without closing it. After the random draw has decided the information to be transmitted to B, we write the corresponding information on the envelope and close it. Then each envelope is given to a randomly chosen B. B receives the envelope and writes his decision on it, without opening it. Finally, all envelopes are collected by the experimenters.

This is the end of the first round of the experiment. After this there will be four [nine] further rounds, in each of which you will be randomly matched with a different participant. We will ensure that you will be matched with five [ten] different participants during the five [ten] rounds.

[This paragraph only in the treatment without noise.] The decisions are marked on a separate decision sheet, which we are going to hand out to all participants with the role A in a moment. A indicates on the sheet the alternative he chooses. After this the experimenters hand the sheet to a randomly selected B. Knowing the decision of A, B makes his decision.

After each of the five [ten] rounds all participants are informed about the outcome of their round.

To guarantee anonymity you receive a code number. Please keep your code card carefully, because you will only obtain your payoff by showing this card. In addition to this, the code number ensures your anonymity to us and the participant you are matched with.

Your total payoff is the sum of the single payoffs of the five [ten] rounds. In addition to this you will receive DM 5 [DM 10] independent of the outcome of the rounds.

You have the role A [B].

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