

Arms or Legs: Isomorphic Dutch Auctions and Centipede Games

By James C. Cox and Duncan James

Arms or Legs: Isomorphic Dutch Auctions and Centipede Games¹

Centipede games and Dutch auctions provide important instances in which game theory fails empirically. The reasons for these empirical failures are not well understood. Standard centipede games and Dutch auctions differ from each other in terms of their Institutional Format (IF), Dynamic Structure (DS), and Information Environment (IE). This paper introduces new games that are constructed from centipede games and Dutch auctions by interchanging some of their IF, DS, and IE characteristics. The new games are introduced in isomorphic pairs. Experiment treatments with pairs of new isomorphic games provide data that yield insights into the effects on behavior of games' IF, DS, and IE characteristics. (JEL C72, C91, D44)

1. Introduction

Dutch auctions and centipede games both exhibit systematic deviations of behavior in experiments from predictions of game theory. Theory for the centipede game predicts unraveling to a “take” at the first node in the game tree but failure of this prediction for the traditional two-person, extensive form of the game is a robust empirical phenomenon (McKelvey and Palfrey, 1992, 1998; Zauner, 1999). Theory predicts that the Dutch auction is isomorphic to the first price sealed bid auction but prices in a fast-clock Dutch auction are lower and prices in a slow-clock Dutch auction are higher than prices in comparable first price sealed bid auctions (Cox, Roberson, and Smith, 1982; Cox Smith and Walker, 1983; Lucking-Reilly, 1999; Katok and Kwasnica, 2008). The reasons for these empirical failures of theory are not well understood. This paper seeks better understanding of the determinants of behavior in centipede games and Dutch auctions by studying new games constructed by interchanging some of the games' typical characteristics.

Standard centipede games and Dutch auctions differ from each other in terms of their Institutional Format (IF), Dynamic Structure (DS), and Information Environment (IE). The IF of a standard centipede game is an extensive form game tree whereas the IF of a standard Dutch auction is a price clock. The DS of a standard centipede game is alternating opportunity to select an action (take or pass) whereas the DS of a standard Dutch auction is simultaneous opportunity

¹ Financial support was provided by the National Science Foundation (grant numbers IIS-0630805 and SES-0849590). Helpful comments and suggestions were provided by Amnon Rapoport.

to select an action (bid or don't bid). The IE of a standard centipede game is public information on (money) payoffs whereas the IE of a standard Dutch auction is private information on payoffs (because auctioned item values are private). This paper introduces new games that are constructed by interchanging some of the IF, DS, and IE characteristics of the standard games. The paper reports an experiment with the new games that provides insight into which characteristics of games are empirically significant determinants of behavior and which of these significant characteristics account for systematic differences between theory and behavior.

We construct modified centipede games that have the same IE as standard Dutch auctions: the independent private values environment in which an agent knows her own payoffs but only the probability distribution of others' payoffs for all decision opportunities. We use independent private values (IPV) rather than public information (PI) about payoffs because: (a) the unraveling prediction for centipede games is robust to IPV; but (b) the Nash equilibrium bid functions for Dutch auctions are *not* robust to PI about auctioned item values. We construct modified Dutch auctions that have the same DS as standard centipede games: alternating (rather than simultaneous) opportunities to bid or not bid. We construct modified centipede games that have the same DS as standard Dutch auctions: simultaneous (rather than alternating) opportunities to take or pass. We construct modified centipede games that have the same IF as standard Dutch auctions: a decreasing price clock. Finally, we construct Dutch auctions with the IF that characterizes standard centipede games: an extensive form game tree. The paired clock and tree formats for the modified Dutch auctions are theoretically isomorphic. A theoretical isomorphism also holds for the paired clock and tree formats of the modified centipede games. Because the paired games are strategically equivalent, any significant differences in behavior between them are caused by behavioral significance of characteristics of games that are not captured by existing theory of equilibrium strategies.

2. Related Literature

There is a substantial literature on experimental tests of the theory of Dutch auctions and centipede games. We review a few papers.

2.1 Dutch Auctions

In his book on the history of auctions, Cassady (1967) discusses auction market formats that have been used for long historical periods. He defines “Dutch auction” as follows (Cassady, 1967, p. 67):

In this auction the offer price starts at an amount believed to be higher than any bidder is willing to pay and is lowered by an auctioneer or a clock device until one of the bidders accepts the last offer. The first and only bid is the sales price in the Dutch auction.

One implication of this institutional format is that any bidder who stops the auction near the beginning is likely to lose money. This is the defining characteristic of “Dutch auction” that we do *not* change when new modified versions are introduced by changing the standard game’s IF and DS characteristics.

Vickrey (1961) first explained that the Dutch auction is theoretically isomorphic to the first price sealed bid auction in the IPV information environment. This implies that the Nash equilibrium bid function is the same function for these two auctions even though the Dutch auction has a decreasing price clock, real-time institutional format whereas the first price sealed bid auction has a normal form game format. Cox, Roberson, and Smith (1982) tested this isomorphism using a Dutch auction digital price clock with two-second price decrement speed.² They reported that the isomorphism failed empirically; the Dutch auction produced lower prices than the first price auction in laboratory experiments using (induced) independent private values.

² Dutch flower auctions use very fast clock speeds. Characteristics of the biggest flower auction institution are reported at <http://www.aalsmeer.nl/00004.asp>.

Cox, Roberson, and Smith offered two “real time” models of the Dutch auction, using non-standard assumptions, both of which were consistent with lower prices in the Dutch auction than in the first price auction. One model incorporated a utility from the activity of playing the game that was additive to the utility of money payoff from bidding whereas the other model incorporated biased application of Bayes’ rule in updating bidders’ expectations about rivals’ bidding behavior during an auction. Cox, Smith, and Walker (1983) reported an experimental test of the alternative models which led to rejection of the utility of playing the game model in favor of the biased Bayes’ rule model.

Lucking-Reiley (1999) reported an internet experiment with uncontrolled information environment (concerning item values) and an extremely slow Dutch price clock. He found that the Dutch and first price auction isomorphism failed but that Dutch prices were higher than prices in the first price auction. Katok and Kwasnica (2008) reported an experiment in the IPV information environment in which Dutch auction clock speed was a treatment variable. They reported that the isomorphism failed and that Dutch auction prices were lower (respectively, higher) than prices in the first price auction with a fast (respectively, slow) Dutch price clock. The clock format Dutch auctions and centipede games reported below use a 10-second price clock speed, which is in the middle of the clock speeds used as treatment variables by Katok and Kwasnica (the other two speeds they used were one-second and 30-seconds). Our tree format centipede games and Dutch auctions use a comparable 10-second decision opportunity at each node in the extensive form game tree.³

³ Turocy, Watson, and Battalio (2007) replicated the result that prices are lower in Dutch auctions than in (theoretically-isomorphic) first price auctions using a Dutch auction clock speed that was calibrated to approximately equate the total time used by subjects in experiments with either 60 first price auctions or 60 Dutch auctions.

2.2 Centipede Games

In a standard centipede game, the payoff of each player is positive at his first decision node. This is the defining characteristic of “centipede game” that we do *not* change when new modified versions are introduced by changing the standard game’s IF and IE characteristics. The centipede game is typically implemented in a public information environment in which the payoffs of all players at all decision nodes are public information. A sequential move structure is standard. Each player has his own decision nodes to choose “take” or “pass.” If a player chooses the action “pass,” this leads to an increase in the sum of payoffs across players but hands the next “take” opportunity to the other player.

A typical centipede game included in McKelvey and Palfrey (1992) is shown in Figure 1 (with payoff of agent 1, or “you” in bold).

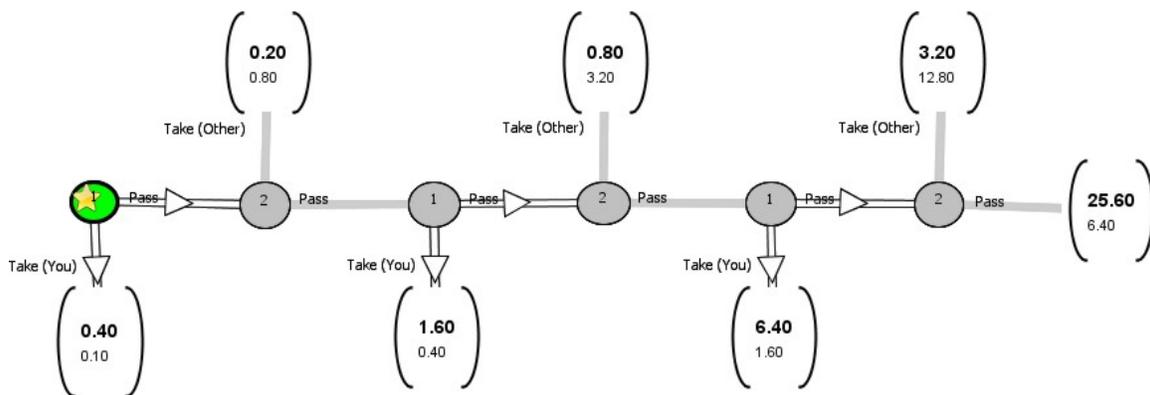


Figure 1. A Typical McKelvey and Palfrey Centipede Game

These payoffs differ from those modeled by Aumann (1995) in a notable way; the *final* node payoffs in Aumann’s centipede game are zero for every player. In contrast, the *total* payoff to all players in a typical McKelvey and Palfrey centipede game increases throughout the game. The choice of final node payoffs in our centipede games is determined by the pairing with Dutch auctions. If the Dutch auction price clock ticks to zero (or to a positive seller reserve price)

without any bidder choosing to buy then all bidders receive zero surplus. Hence the natural pairing of centipede games with Dutch auctions is to set all players' payoffs to zero at the final node in a centipede game, as in Aumann's (1995) game.

The centipede game presents a tension between what economists might suppose to be an agent's wish to obtain a higher payoff for himself, by waiting to take, and a desire to avoid getting zero (or a low) payoff by waiting so long that the other player takes first. This tension within an agent, and the potential for each agent to develop beliefs about this tension (and other possible motivations) in other agents makes the centipede game a potential test-bed for hypotheses on a range of subjects.

For instance, does the predicted subgame perfect outcome (taking at the first node) occur in experiments? McKelvey and Palfrey (1992) found that generally it did not. What are the implications of such observations? Can failure to play according to the theoretical prediction be taken as evidence of altruism, decision errors, or beliefs that other altruistic or error-prone agents might be present in the population from which opponents are drawn? A number of researchers have attempted to explain the disparity between the empirical results and the theoretical prediction using one or another such explanation. McKelvey and Palfrey (1992) discussed the possibility that subjects' altruism could explain the empirical failure of the unraveling prediction. In a subsequent paper, McKelvey and Palfrey (1998) examined the explanatory possibilities of a particular error-in-choice model, quantal response equilibrium. Zauner (1999) examined the possibility that "independent perturbed payoffs" could explain the data (and estimated the magnitude of noise in perceived payoffs needed to do so).

Fitting new models to data from a particular game is one way to attempt to understand what is going on in that kind of game. Another approach is to vary characteristics of the game in order to assess their significance as determinants of behavior. Rapoport, Stein, Parco, and Nicholas (2003) varied parameters of the design of the centipede game (such as the number of players and the magnitude of the payoffs) in order to assess whether the traditional result of

failure to unravel was still observed. They reported that moving from two to three players and increasing the size of payoffs appeared to increase the incidence of unraveling. Further work by Murphy, Rapoport, and Parco (2006) investigates the effect of moving from $n=3$ to $n=7$ players, and of changing the proportions according to which total payoffs at a node are allocated across the one “winner” and the $n-1$ “losers.” They find a strong effect from the increase in numbers and a milder effect from the change in allocation of payoffs. Our paper also takes the approach of varying characteristics of the game in order to better understand its properties. Our paper differs from Rapoport, et al. (2003) and Murphy, et al. (2006) in that we focus on systematic variation in institutional format and dynamic structure rather than variations in number of players or size of the total payoff for all players or the split of total payoff across winners and losers.

In order to identify the role of institutional format, it is necessary that an exact correspondence in message spaces across isomorphic games be maintained. This design principle, already put forth for the comparison of the Dutch auction and the first price sealed bid auction by Cox, Roberson, and Smith (1982), is similarly applicable to IPV centipede games presented in different institutional formats (i.e. clock versus tree). Thus we compare tree format to clock format while holding constant dynamic structure (encompassing sequential/alternating versus simultaneous move structure), payoff incrementation per discrete unit of time, and number of players. We also compare simultaneous move structure to sequential/alternating move structure while holding constant institutional format, payoff incrementation per discrete unit of time, and number of players.

Our paper contributes to the literature by experimenting with the effects of changes in institutional format, dynamic structure, and information environment in new games derived from standard centipede games and Dutch auctions. If changes in IF, DS, or IE produce significant changes in behavior, this would suggest that parameters from models such as quantal response equilibrium or independent perturbed payoffs would have to vary across different representations of the same game, thus leading one to reflect upon the generality of those models. We look at

both Dutch auctions and centipede games in the same study because this allows us to ascertain if any dependence of bids or takes on IF, DS, or IE characteristics generalizes across games. Additionally, it should be noted that complete unraveling of the centipede game (however parameterized) with only two players and few repetitions would be a new type of empirical result.

2.3 Maintained Difference between Dutch Auctions and Centipede Games

Our experiment implements modified forms of Dutch auctions and centipede games that are constructed by changing some of the IF, DS, and IE characteristics of the traditional games. This suggests the question of what characteristic(s) of the modified games separate centipede games from Dutch auctions. We maintain one distinction between the two types of games: the games are always parameterized so that theory predicts unraveling to the first decision opportunity (tree node or clock tick) in any centipede game whereas theory predicts interior (to the decision space) Nash equilibrium in any Dutch auction.

2.4 Varying Game Forms

What accounts for the failure of Nash equilibrium bidding theory to predict prices in Dutch auctions? Previous literature has offered two explanations: (a) underestimation of the risk of letting the clock continue to run as, for example, in the Bayes' rule miscalculation model (Cox, Roberson, and Smith, 1982; Cox, Smith, and Walker, 1983); and (b) bidder impatience as, for example, in the model in Katok and Kwasnica (2008). The sequential bid form of the Dutch auction that we implement may make the risk from letting the clock continue to run be more salient. Furthermore the sequential bid form of the Dutch auction may make impatience more pronounced by doubling (from one to two) the number of clock ticks between successive bid opportunities. Our experimental design does not address the distinction between the possible effects of Bayes rule violation and impatience. Instead, we ask whether failure of Nash equilibrium bidding theory is robust to changes in the IF and DS of the bidding game.

What accounts for the empirical failure of the unraveling prediction in standard centipede games? Is it the public information environment, which makes salient the exact opportunity cost of the other player from passing at each node? We introduce the independent private values form of the centipede game, which makes it impossible for a player to know the other player's exact opportunity cost at any decision node but preserves the pattern of increasing opportunity costs for both players. And, just as we do with the Dutch auction, we vary the IF and DS of the game to see whether failure of the subgame perfect equilibrium prediction is robust to such changes.

3. Clock and Tree Formats with Sequential or Simultaneous Moves

We explain clock and tree formats of Dutch auctions and centipede games with independent private values. Each (clock or tree) format of the Dutch auction or centipede game is developed with alternative dynamic structures involving sequential or simultaneous move (bid or take) opportunities.

3.1. Sequential-Move Dutch and Centipede Clock Games

The sequential-bid Dutch auction with clock format is simply the traditional Dutch auction with the one change that the bidders alternate price clock ticks at which they are allowed to bid. That is, for a given clock reading, only one bidder has the right to bid at that clock price; the other bidder(s) would have to wait until the clock counts down to their turn before they would have a chance to bid. In the two-bidder, \$1.00 price decrement case we utilize in our design, the price on the clock starts at 11 and one bidder can bid at price clock readings of 10, 8, 6, 4, or 2 while the other bidder can bid at clock readings of 9, 7, 5, 3, or 1. The bidders' private values for the auctioned item are independently drawn from the uniform distribution on $[1.01, 1.02, \dots, 10.99, 11.00]$, which supports an interior Nash equilibrium (as shown below in section 4.1). This version of the Dutch auction is presented to bidders as shown in Figure 2 (for the first price tick).

Period #1
Status: Bidding

Auction: Dutch*

The auction price decreases until a bidder clicks on the Purchase button. The first bidder to click on the Purchase button buys the item at the current price shown when that bidder clicks on the button.

Total Profit: 0.00
Total Purchases: 0

Bidding Information

Your value: **8.53**

Starting price: **11.00**

Number of bidders: 2

Bidding

Current price: 10.00

Purchase

Previous Auctions

Period	Auction	Final Price	Your Value	Your Highest Bid	Period Profit	Accumulated Profit

Figure 2. Clock Format Sequential Bid Dutch Auction

The sequential-take IPV centipede game with clock format maintains the DS of alternating decision opportunities that characterizes the traditional game but incorporates that DS into a price clock IF. The IPV centipede game in clock format (and tree format) replaces the public information IE of the traditional centipede game with private information about players' payoffs. In the two-player, \$1.00 price tick decrement game we utilize in our design, one player can take at price clock readings of 10, 8, 6, 4, or 2 while the other player can take at price clock readings of 9, 7, 5, 3, or 1. The players' private values are independently drawn from the uniform distribution on [11.01, 11.02, ..., 20.99, 21.00], which supports an unraveling prediction (as shown below in section 4.4). This version of the centipede game is presented to subjects exactly as the clock auction shown in Figure 2, except the players' private values (seen in the upper left of the display) would be higher (specifically, between 11.01 and 21.00).

3.2 Sequential-Move Centipede and Dutch Tree Games

We use an IPV information environment for our version of the sequential-take centipede game in tree format (as well as clock format). Each player has an initial value drawn from a uniform distribution on $[0.01, 0.02, \dots, 9.99, 10.00]$, to which an amount n is added at each subsequent decision node $n = 1, 2, \dots, 10$, which supports an unraveling prediction (as shown in section 4.3). A player's payoff from taking at node n (when possible) is $v_j + n$, where v_j is the player's private value. Each player can only see that the other player has some unknown initial value "not i ," to which is added \$2.00 at each of the subsequent *other player's* decision nodes. The centipede game in tree format is presented to the subjects as shown in Figure 3 (with "live" decision node indicated by the star at the first node). With each "pass" the star indicating live node moves to the right.

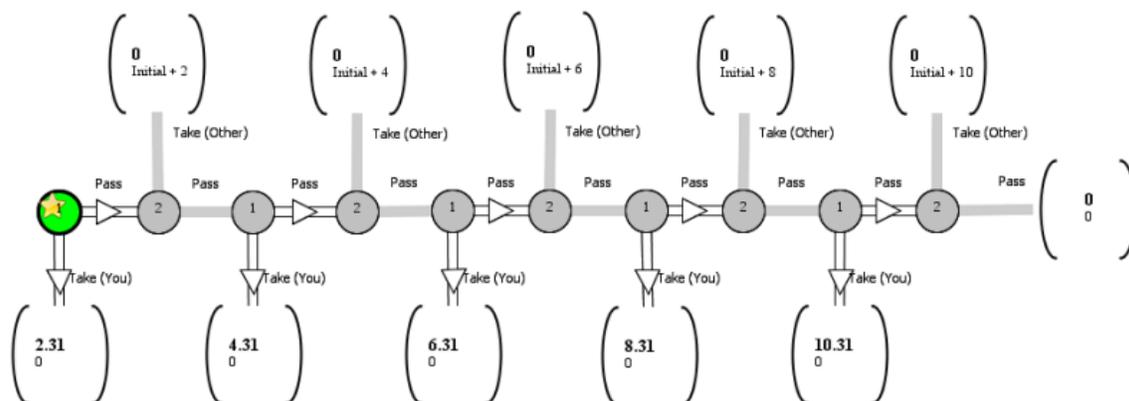


Figure 3. Tree Format Sequential Move Centipede Game

The sequential-bid Dutch auction in tree format (as well as clock format) uses the DS of alternating bid opportunities instead of the simultaneous bid opportunities of the traditional Dutch auction. The tree format Dutch auction represents the auction with an extensive form game tree rather than a price clock. Each bidder has an initial value drawn from the uniform distribution on $[-9.99, -9.98, \dots, -0.01, 0.00]$, to which an amount n is added at each subsequent decision node

n , which supports an interior Nash equilibrium (as shown in section 4.2). A bidder's payoff from bidding at a node n (when possible) is $v_j + n$, where v_j is the bidder's private value for the auctioned item. As in traditional IPV Dutch auctions (Vickrey, 1961), each bidder knows his own auctioned item value but only knows the distribution from which the other bidder's value is drawn. The Dutch auction in tree format is presented to the subjects exactly as the centipede game in Figure 3, except the payoffs are lower (specifically, they are consistent with v_j being between -9.99 and 0.00).

3.3 Simultaneous-Move Dutch and Centipede Clock Games

The simultaneous-bid Dutch auction in clock format is the standard form of that auction. The simultaneous-take IPV centipede game in clock format differs from the standard centipede game in IF, DS and IE: the clock format is used; each player can take at every node; and players' payoffs are private information.

3.4 Simultaneous-Move Centipede and Dutch Tree Games

The simultaneous-bid Dutch auction in tree format differs from the standard Dutch auction only in its IF: a tree format is used rather than a clock format. The simultaneous-take IPV centipede game with tree format, shown in Figure 4, differs from the standard centipede game in DS and IE: each player can take at every node and players' payoffs are private information.

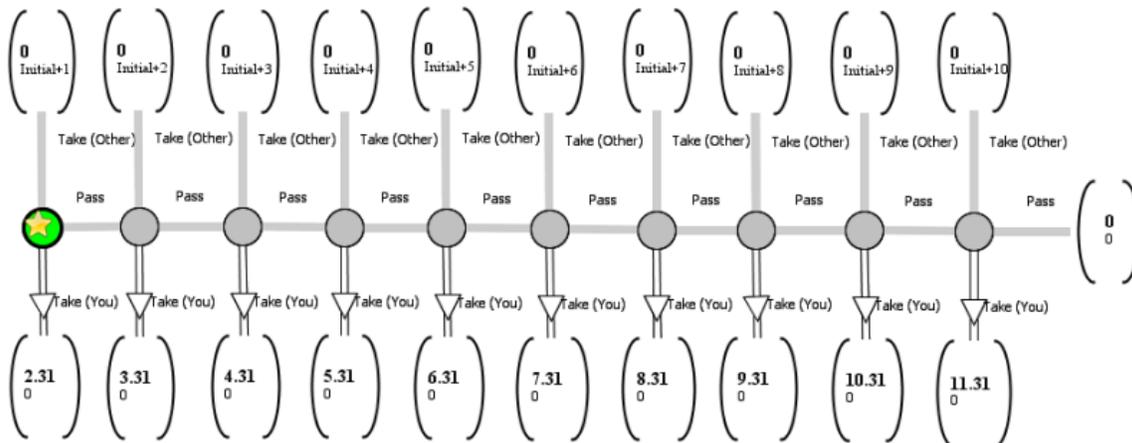


Figure 4. Simultaneous Move Tree Format Games

4. Theoretical Predictions

For the two games in each pair to be isomorphic, they need to have the same dynamic structure. Implementing this structure entailed a list of features. First, we made the role of time identical across clock format and tree format; that is, both formats allowed subjects 10 seconds at a given price clock reading or decision node in the tree in which the subject could click with a mouse to bid or take.⁴ If at the end of 10 seconds the subject had not bid or taken, the game advanced to the next price clock reading or decision node in the tree; the subject could not actively select “not to bid” or “not to take” but could only do so by waiting 10 seconds for the computer to advance the game. Second, we set the change in payoff from one decision opportunity to the next one (belonging to the other player) equal to \$1.00 across all games in all sessions. Third, all games were constructed so as to have a default setting of zero payoffs for both players in the event of “no bid” in the auction or “no take” in the centipede game. We did this because we needed the same end-of-game payoffs across games to preserve isomorphism and because the default of “no transaction” is what is natural for Dutch auctions. Also, the fact that some existing centipede

⁴ Data reported in Katok and Kwasnica (2008) make clear that clock speed affects outcomes in Dutch clock auctions. This suggests that clock speed could affect outcomes in centipede clock games and that node decision time could affect outcomes in Dutch and centipede tree games.

experiments were structured with a (0,0) terminal node encouraged us in settling on this standardization.

4.1 Predictions for the Sequential-Bid Dutch Auction with Clock Format

In our sequential Dutch auction with clock format, the odd-price bidder can bid at clock prices of 9, 7, 5, 3, and 1. The even-price bidder can bid at clock prices of 10, 8, 6, 4, and 2. The two bidders' values for the auctioned item are independently drawn from the uniform distribution on $[1.01, 1.02, \dots, 10.99, 11.00]$. The item values and bids are (of necessity) discrete, hence the bid functions are step functions. The risk neutral Nash equilibrium bid functions for odd-price bidder and even-price bidder are as follows. Let $b_s^o[l_s^o, h_s^o]$ denote that values in the range $[l_s^o, h_s^o]$ support a Nash equilibrium bid of b_s^o on the Dutch price clock by the odd-price bidder, for whom $b_s^o \in \{9, 7, 5, 3, 1\}$. Similarly, let $b_t^e[l_t^e, h_t^e]$ denote that values in the range $[l_t^e, h_t^e]$ support a Nash equilibrium bid of b_t^e on the Dutch price clock by the even-price bidder for whom $b_t^e \in \{10, 8, 6, 4, 2\}$. No values support bids of 9 or 7 by the odd-price bidder. Similarly, no values support bids of 10 or 8 by the even-price bidder. The other parts of the of the Nash equilibrium bid functions are:

Odd-price Bidder: 5[7.25, 11.00], 3[3.59, 7.24], 1[1.01, 3.58]

Even-price Bidder: 6[9.32, 11.00], 4[5.41, 9.31], 2[2.00, 5.40]

The bid functions were solved for numerically. The numerical procedure consists of:

(1) Initializing each bidder's probability of bidding at each of the ten clock prices at which they can bid at 1/10.

(2) Calculating the expected value maximizing bids for each bidder, given the probabilities of winning (at each price) implied by the opposing bidder's probabilities of bidding in step (1).

(3) Updating the probability of bidding at a given price (for each bidder) based on the expected value maximizing bids in step (2).

(4) Looping through steps (2) and (3) until mutual best response bid functions are obtained for both bidders.

4.2 Predictions for the Sequential-Bid Dutch Auction with Tree Format

The odd-price bidder and even-price bidder Nash equilibrium bid functions for the tree-format sequential Dutch auction are a translation of the clock-format bid functions, as can be seen from the following. Let $X_j, j = 1, 2$, denote the random variables for the two bidders' item values in the clock format auction. Let $x_j, j = 1, 2$, denote the two bidder's realized values in the auction. Bidder j knows that her own payoff from bidding at price clock tick t when it is her turn is $x_j - 11 + t$ (because the clock price is 10 at tick 1). Bidder j does not know bidder k 's ($k \neq j$) payoff from bidding at any permissible tick τ ; instead, it is the random variable $X_k - 11 + \tau$.

Let $Y_j, j = 1, 2$, denote the random variables for the two bidders' item values in the tree format Dutch auction and let $y_j, j = 1, 2$, denote their realized values. Bidder j knows that his own value from bidding at any node n (when it is his turn) is $y_j + n$. Bidder j does not know bidder k 's ($k \neq j$) value from bidding at node η ; instead, it is the random variable $Y_k + \eta$.

The clock format and tree format Dutch auctions are isomorphic in the following sense. At tick $t = s$ and node $n = s$, the random payoffs from bidding in the clock and tree format auctions are, respectively, $X_j - 11 + s$ and $Y_j + s$. Recall that X_j is uniformly distributed between 1.01 and 11.00 whereas Y_j is uniformly distributed between -9.99 and 0.00. Therefore, at any tick = node = s , the probability distributions of $X_j - 11 + s$ and $Y_j + s$ are identical and

hence the probability distributions of bids are predicted to be identical in the clock and tree format Dutch auctions.

4.3 Predictions for the Sequential-Take IPV Centipede Game with Tree Format

The tree format centipede game with sequential take opportunities and independent private values has a subgame perfect equilibrium similar to that associated with the traditional public value centipede game. This can be seen as follows. Let the two players have any two values, v_1 and v_2 drawn from the support $[0.01, 0.02, \dots, 9.99, 10.00]$ for the uniform distribution of values. This creates a situation where player 1 could earn v_1+1 at her first take node, v_1+3 at her second take node, or v_1+5 , v_1+7 , or v_1+9 at her successive take nodes, while the second mover could earn v_2+2 , v_2+4 , v_2+6 , v_2+8 , or v_2+10 at her take nodes. The player who does not take earns zero at all nodes. If neither player has taken by the time the second player's final take node has timed out (after 10 seconds), both players earn zero. This suggests that if the second player's final take node were to be reached, the second player would take and would earn v_2+10 while the first player would receive zero. A rational first player would anticipate this, and take at the preceding node; but a rational second player would anticipate this, and take at the preceding node, and so on. This argument leads to prediction of a take at the first node. Therefore, the theoretical prediction for the IPV centipede game is unraveling to a take at the first node, the same as theory predicts for the traditional centipede game with public values.

4.4 Predictions for the Sequential-Take IPV Centipede Game with Clock Format

The same (unraveling) subgame perfect equilibrium applies to the clock format centipede game, as shown by the following. Let Y_j , $j=1,2$, denote the two players' random values in the tree format centipede game and let X_j , $j=1,2$, denote their values in the clock format game. Let

y_j and x_j , $j=1,2$, denote the players' realized values. Player j knows that his own payoff from taking at node n in the tree game (when it is his turn) is $y_j + n$. Player j does not know player k 's ($k \neq j$) payoff from taking (when permitted) at node η in the game tree; instead, it is the random variable $Y_k + \eta$. Similarly, player j 's payoff from taking at tick t in the clock format centipede game is $x_j - 11 + t$ (because the price on the clock is 10 at tick 1). Player j knows that player k 's ($k \neq j$) payoff from taking at tick τ in the clock format game is the random variable $X_k - 11 + \tau$.

The tree format and clock format IPV centipede games have the same (unraveling) equilibrium because of their different uniform distributions of values. At node $n = s$ and tick $t = s$, the random payoffs from taking in the tree format and clock format games are, respectively, $Y_j + s$ and $X_j - 11 + s$. Recall that Y_j is uniformly distributed between 1.01 and 11.00 whereas X_j is uniformly distributed between 11.01 and 21.00. Therefore, at any node = tick = s , the probability distributions of $Y_j + s$ and $X_j - 11 + s$ are identical.

4.5 Predictions for the Simultaneous-Bid Dutch Auction with Clock Format

The risk neutral bid function for the simultaneous-bid Dutch with clock format and values drawn from a uniform distribution on [1.01, 1.02, ..., 10.99, 11.00] and with each player able to bid at 10, 9, 8, 7, 6, 5, 4, 3, 2, or 1 are as follows. Let $b_s[l_s, h_s]$ denote that values in the range $[l_s, h_s]$ support a Nash equilibrium bid at price b_s on the Dutch price clock. No values support bids of 10, 9, 8, 7, or 6. The other parts of the of the Nash equilibrium bid function are:

Both Bidders: 5[7.67, 11.00], 4[6.46, 7.66], 3[4.16, 6.45], 2[2.47, 4.15], 1[1.01, 2.46]

The bid function was solved for numerically. This was done by applying the FindRoot routine in Mathematica 6.0 to a system of equations embodying conditions 1 through 4 in Chwe (1988).

Chwe's conditions 1 through 4 characterize the pure strategy Nash equilibrium bid function in a first price sealed bid auction with a discrete bid space. Our numerical solution satisfies the inequalities in Chwe's Proposition 1. The theoretical isomorphism between the first price sealed bid auction and the Dutch auction is then invoked to apply that solution in the present setting.

4.6 Predictions for the Simultaneous-Bid Dutch Auction with Tree Format

Arguments similar to those in subsections 4.2 and 4.5 can be used to derive the Nash equilibrium bid function for the simultaneous-bid Dutch auction with tree format. With initial values X_j , $j = 1, 2$ drawn from the uniform distribution on $[-9.99, -9.98, \dots, -0.01, 0.00]$ and payoffs for exiting at node n given by X_{j+n} , the Nash equilibrium strategy function is as follows. Let $t_n[l_n, h_n]$ denote that values in the range $[l_n, h_n]$ support a Nash equilibrium take at node n . No initial values correspond to taking at any of the first five nodes. The other parts of the Nash equilibrium strategy function are:

Both Bidders: 6 $[-3.33, 0.00]$, 7 $[-4.54, -3.34]$, 8 $[-6.84, -4.55]$, 9 $[-8.53, -6.85]$, 10 $[-9.99, -8.54]$

4.7 Predictions for the Simultaneous-Take IPV Centipede Game with Tree Format

The tree format centipede game with simultaneous take opportunities and independent private values has a subgame perfect equilibrium similar to that associated with the traditional public value centipede game with sequential take opportunities. This can be seen as follows. Let the two players have any two values, v_1 and v_2 drawn from the support $[0.01, 0.02, \dots, 9.99, 10.00]$ for the uniform distribution of values. This creates a situation where player a would earn $v_a + t$ if she takes at node $t = 1, 2, \dots, 10$ while player b would earn $v_b + t$ if he takes at node t . The player who does not take earns zero. If both players try to take at the same node, the probability that either succeeds in taking (by entering the take response first) is $1/2$. If neither player has taken by

the time the final take node has timed out (after 10 seconds), both players earn zero. Therefore if node 10 (the final take node) were to be reached, both players would want to take at that node, and the probability that either would succeed would be $1/2$. A rational player would anticipate this, and consider the expected payoff from taking at node 9. If player k does *not* try to take at round 9 then player j prefers to take because she would succeed with probability 1 and receive payoff $v_j + 9$, which is greater than the expected payoff from waiting until node 10, which is $1/2 \times (v_j + 10)$. If player k does try to take at round 9 then player j prefers to take because she would succeed with probability $1/2$ and receive expected payoff $1/2 \times (v_j + 9)$, which is greater than the zero amount that would be received from not trying to take at round 9. Therefore each player prefers to take rather than pass at round 9. Similar reasoning shows that each player prefers to take rather than pass at round 8, and so on back to round 1. Therefore, the theoretical prediction for the simultaneous move IPV centipede game is unraveling to a take at the first node, the same as theory predicts for the traditional centipede game with sequential moves and public values.

4.8 Predictions for the Simultaneous-Take IPV Centipede Game with Clock Format

Arguments similar to those in subsections 4.3 and 4.7 can be used to derive the subgame perfect equilibrium strategy function for the simultaneous-take centipede game with clock format. Initial values x_j , $j = 1, 2$, are drawn from the uniform distribution on $[11.01, 11.02, \dots, 20.99, 21.00]$ and payoff is $x_j - p_j$ for taking at clock tick t , with price equal to $p_t = 11 - t$, for Reasoning as above leads to the conclusion that play unravels to a take at the first tick of the price clock at a price equal to 10.

5. Experiment Design

In this section we describe details of the experiment design. In section 3 we described how to implement two (isomorphic) versions of each game. We now explain how non-essential differences across different games are eliminated by judicious parameterization. We present a matrix of treatments and a discussion of treatment sequencing to show how all of this allows for an assessment of how observed behavior can be inconsistent with theoretical isomorphisms and how such inconsistencies, if observed, can be attributed to behavioral properties of alternative institutional formats.

In addition to design choices intended primarily to hold constant dynamic structure across institutional formats, we also made certain design choices in order to minimize the differences in parameterization across treatments. We did this so as to minimize potential sources of confounds. First, we used an 11 tick clock or 11 node tree in every treatment. Second, all games utilized an independent private values information environment; again, this removes a potential confounding difference for interpreting results across games. Third, all games utilized a uniform distribution with a support width of \$10.00 as the source of independent private values; again, this standardization removes an impediment to comparisons across games. Finally, it should be pointed out that when all of these design choices were implemented, it left a design where all it took to switch between the sequential Dutch auction and the IPV centipede game was a \$10.00 shift in the location (low value, high value, or midrange) of the \$10.00 wide uniform distribution used to generate independent private values.

The experiment design implements two key objectives. First, the design can detect inconsistencies with theoretical isomorphisms – between the clock and tree formats of the Dutch auction and between the clock and tree formats of the IPV centipede game. Second, the design allows us to ascertain whether any such violation can be attributed to institutional format; in particular, the design allows us to ascertain whether any difference between clock and tree

formats is similar or dissimilar in Dutch auctions and centipede games. The experiment includes the treatments listed in Table 1.

Table 1. Experiment Treatments

	Sequential IPV Centipede Games	Sequential Dutch Auctions	Simultaneous IPV Centipede Games	Simultaneous Dutch Auctions
Tree Format	Treatment 1	Treatment 3	Treatment 5	Treatment 7
Clock Format	Treatment 2	Treatment 4	Treatment 6	Treatment 8

If there is a difference in the distributions of bids for Treatment 3 (T3) and Treatment 4 (T4) then the isomorphism across institutional formats of the sequential Dutch auction fails. If there is a difference in the distributions of takes between T1 and T2 then the isomorphism across institutional formats of the sequential-take IPV centipede game fails. If such failure is observed, are there any generalizable regularities associated with that failure? For instance, if different distributions of bids are observed for T3 and T4, which distribution is closer to the Nash equilibrium prediction? If T1 and T2 yield different distributions of takes, which is associated with earlier takes? And does either the clock format or the tree format lead to earlier or later bids or takes across games, such that this aspect of the results would appear to be driven by institutional format rather than characteristics of the games captured by existing theory?

With this in mind, the details of sequencing of our design were as follows. Each experiment session took approximately 2 hours. In each session, we ran subjects through three treatments with 10 rounds in each treatment. No subject participated in more than one session. The first, second, and third sets of 10 rounds are referred to, respectively, as parts 1, 2, and 3. We used the following sequences of treatments in parts 1, 2, and 3: T3-T4-T3, T3-T2-T3, T4-T3-T4, T4-T1-T4, T2-T1-T2, T2-T3-T2, T1-T2-T1, and T1-T4-T1. For example, the first listed treatment sequence consisted of 10 rounds of T3 in part 1, followed by 10 rounds of T4 in part 2, followed by 10 rounds of T3 in part 3. We experimented with these treatment sequences so as to

allow for detection of as full as possible set of potential sequencing effects, and to provide for a variety of across-subjects and within-subjects comparisons to be made. We deliberately did not run T1-T3-T1, T3-T1-T3, T2-T4-T2, or T4-T2-T4 sequences, however. This was because for these latter sequences, the only difference in instructions between treatments is the value support – all other text in the instructions remains the same – and we were concerned that subjects might mistakenly think the instructions were exactly the same, potentially even neglecting to read them.

Other details of the experiment are as follows. We used an integer clock price decrement and node payment increment in all treatments to facilitate quick recognition of payoff information by subjects. We used a 2 to 1 experimental dollar to U.S. dollar exchange rate; this was needed to keep payments affordable if we were going to keep using a \$10.00-wide uniform distribution for value draws. We did not just shrink all numbers by 50% to keep payoffs affordable because we wanted integer payoff changes between decision opportunities, as noted above.

6. Results

Experiment sessions were run in the laboratory of the Experimental Economics Center (ExCEN) at Georgia State University during 2007 - 2008. The data are as follows.

6.1 Sequential Dutch Results

The data show a dramatic difference in behavior across isomorphic versions of the sequential Dutch auction employing different institutional formats. This can be seen in a number of ways. First of all, one can pool data across all sessions for the same treatment (e.g. all rounds from all parts for T4 from all experiment sessions are analyzed as belonging to one distribution) and perform rank-sum tests to ascertain whether we can reject the hypothesis that the distribution of deviations from predictions for T4 is the same as the distribution of deviations from predictions for T3. The rank-sum tests performed on pooled data supports the conclusion that the distribution

of deviations is different across the institutional formats in T3 and T4.⁵ Specifically, we find that such a rank-sum test returns a p-value of 0.0000.

To further illustrate the nature of the results, consider the following plot of market prices (or winning bids) from round 1 of part 1 (for which a rank-sum test of difference in distribution between (all) round 1 data from T4 and (all) round 1 data from T3 gives a p-value of 0.000).

Figure 5 shows bar graphs for the numbers of observations at various market prices (or winning bids) for the clock and tree formats. Auction prices *increase* as one moves up the vertical axis from 0 to 10. Clock ticks for winning bids and tree nodes for successful takes *decrease* up the vertical axis.

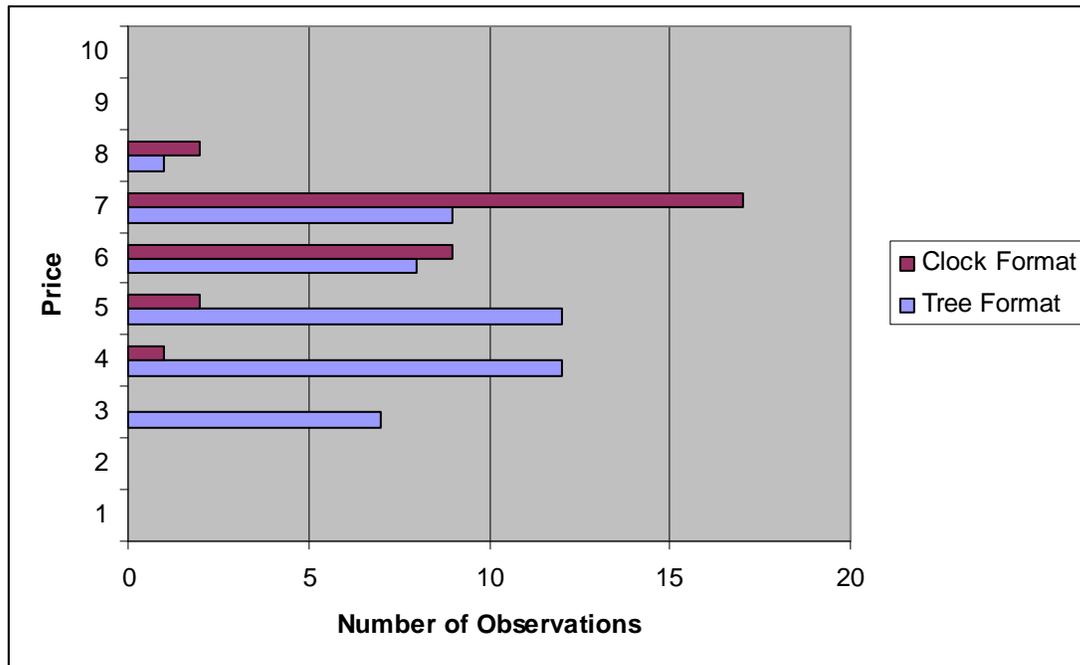


Figure 5. Bids in Sequential-bid Dutch Auctions

⁵ These tests potentially understate the difference between T4 and T3. There are particular rounds where it is practically impossible to detect any difference in behavior across treatments because the drawn values are extremely low for all of the subjects. For example, if the Even bidder has a value of, say 2.47, and the Odd bidder has a value of 1.80, then almost all the data is going to be in the form of a spike at \$2.00 (barring errors) in both treatments. In such a round, it would be impossible to detect a difference in subjects' approach to bidding (across institutional game formats) even if it otherwise existed. Round 5 in Part 1 is one such round.

Clearly the distributions of winning bids are very different across institutional formats, with higher bids observed in the clock format. Note also that in round 1 of part 1, the risk neutral Nash Equilibrium prediction for either format is to bid at 5.

This leads us to our next point: that in addition to comparing behavior across institutional formats, we can compare behavior from a single format to the risk neutral Nash equilibrium predicted bids. For the tree format of the sequential Dutch auction, we find that a p-value of 0.0949 on a rank-sum test on whether the distribution of *deviations from* theoretical predictions in T3 differ from a distribution of zeroes (representing perfect adherence to the theory). The data might best be described as noisily “risk neutral” because the average deviation of all pooled data in T3 is equal to -0.02672. The average deviation from the predicted bid was a little less than three cents (on the side of underbidding) in this experiment in which values were drawn over a \$10.00-wide interval. Rather than picking up any asymmetry relative to the risk neutral prediction, the rank-sum test is instead picking up (to a degree) the substantial, but essentially symmetrical, variance around the prediction that exists in the T3 data.

We can perform a similar analysis for the clock format of the sequential Dutch auction, comparing bids therein to the predictions from section 4.1. In making this comparison, we find that a rank-sum test of whether the distribution of deviations is different from a distribution consisting entirely of zeroes returns a p-value of 0.0000. Here, this reflects consistent overbidding, relative to the prediction, on the part of subjects in T4; the average deviation from the risk neutral Nash prediction (over all of T4) is 0.6545.

Graphically, a time series plot of the average deviation from the theoretical prediction, in each round, for each of T3 and T4, shows both how the results differ across treatments and where they sit relative to the theoretical prediction in each round.

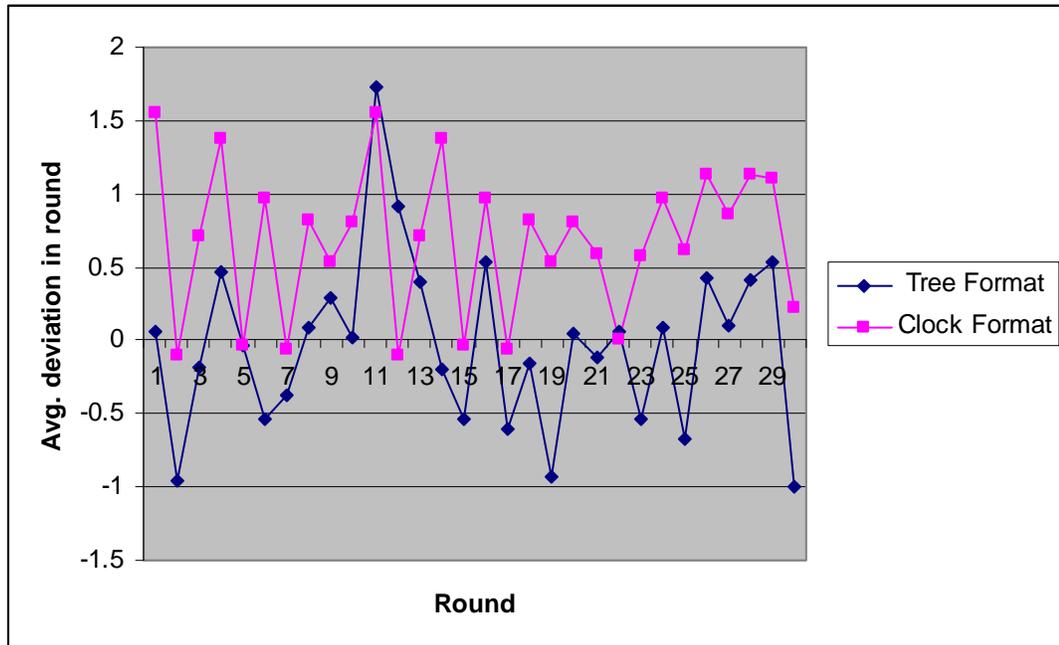


Figure 6. Bid Deviations in Sequential-bid Dutch Auctions

6.2 Sequential IPV Centipede Results

Behavior is also different across institutional formats for the sequential IPV centipede game. Pooling all data across rounds, parts, and sessions, we find that the rank-sum test rejects the hypothesis that the distribution of deviations from predicted takes is the same across institutional formats ($p\text{-value}=0.0000$).⁶

In order to better demonstrate the nature of the results, consider the following plot comparing results across institutional formats within a round (round 1 of part 1). Figure 7 shows bar graphs for the data. The numbers of observations are on the vertical axis. The horizontal axis shows the tree node or clock tick (*not* clock price) at which players first take rather than pass in a centipede game. Successful take nodes (resp., clock ticks) for takes increase from 1 to 10 on the

⁶ Again, this understates the difference across formats. In this case, the reason is that data from both formats demonstrates at least some convergence towards the subgame perfect equilibrium over time; thus pooling all data mixes data from the end of the experiment, when data from both formats exhibit takes near the beginning of the game, with data early in the experiment, when results differ more widely across formats.

horizontal axis. Note that this implies that payoffs for successful takes *increase* to the right along the horizontal axis. The hypothesis that the distributions are the same is rejected with a p-value of 0.000 (for data from round 1, part 1). Clearly, the distributions of take amounts are different across institutional formats.

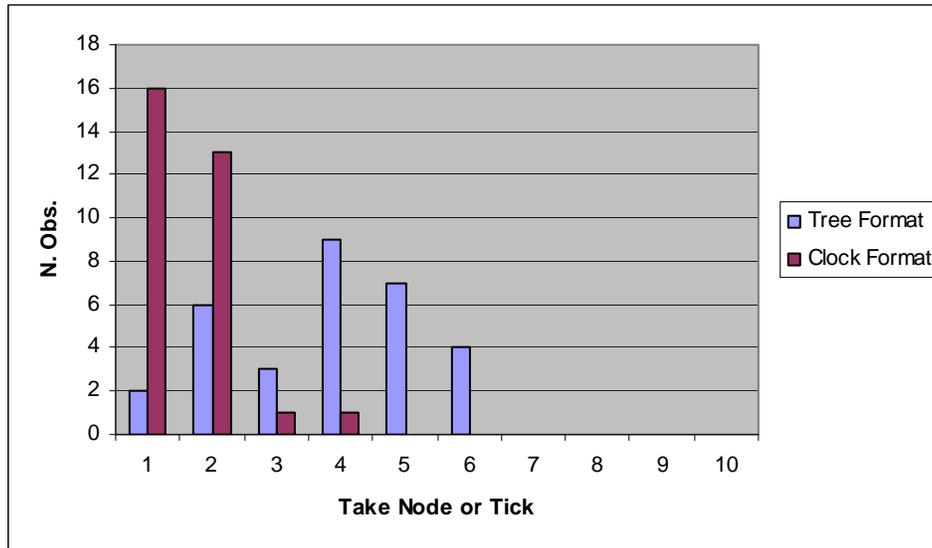


Figure 7. Takes in Sequential-move IPV Centipede Games

Once again, in addition to comparing data across institutional formats, we can also compare data from a single format to the theoretical prediction (of taking at the first node). For the tree format of the IPV centipede game, we reject that the distribution of deviations is indistinguishable from a distribution of zeroes (p-value=0.0000). For the clock format of the IPV centipede game, we also reject that the distribution of deviations is indistinguishable from a distribution of zeroes (p-value=0.0000).

In order to better illustrate the statistical results pertaining to the centipede game, the following graph plots the time series of the average deviation in “take” from the theoretical prediction, for each format.

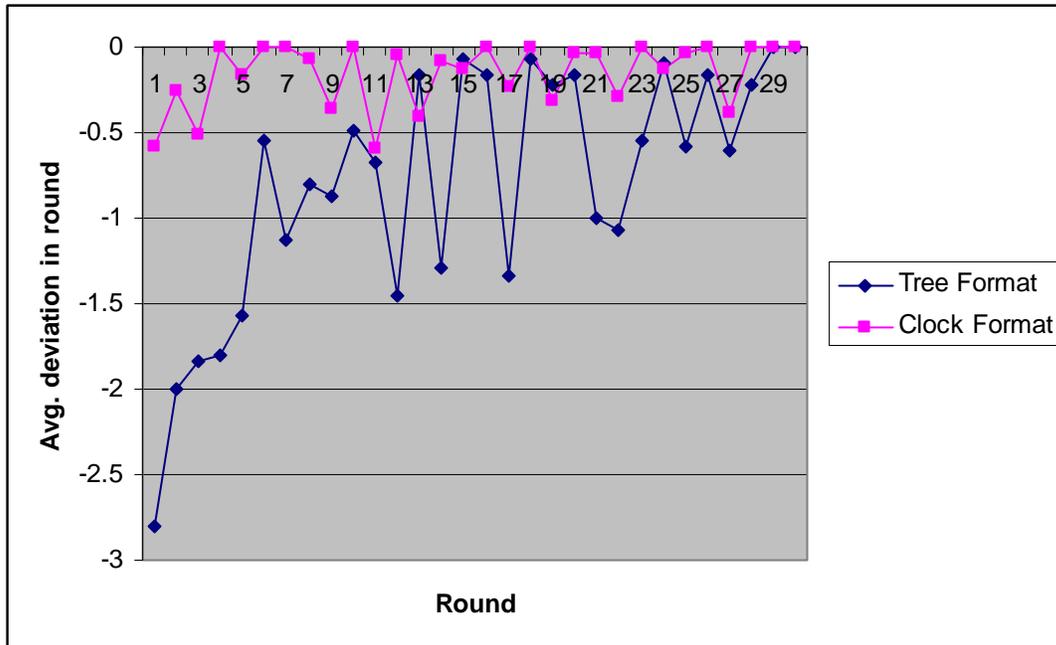


Figure 8. Take Deviations in Sequential-move IPV Centipede Games

In general, we find that the difference in behavior persists until comparatively many repetitions of the game have been completed, at which point T2 starts to reliably achieve the theoretical prediction (in individual rounds) that T1 attained much earlier (in individual rounds). In fact, that T1 was able to attain the theoretical prediction so early when $n=2$ is in itself a novel result in the empirical literature on the centipede game. In addition, we should note that moving to an IPV environment does not in itself eliminate the failure to unravel typical when using the tree format (with $n=2$ and common information); clearly knowing the other player's exact payoff information is not in itself decisive in generating failure to unravel.

Finally, in addition to the striking across-subjects results just discussed, the experimental design allows for within-subjects comparisons to be made as well. The T1-T2-T1 and T2-T1-T2 sessions each allow for a regression analysis in which slope and intercept treatment dummies can detect structural shifts in an underlying time trend (of convergence to the subgame perfect equilibrium).

$$\text{Avg. Node of Take} = a + b_1 \times \text{Time} + b_2 \times \text{Format Dummy} \\ + b_3 \times \text{Time} \times \text{Format Dummy} + \varepsilon_t$$

For the T2-T1-T2 case we find that there are significant changes between treatments. An F-test for coefficients jointly zero rejects that the slope and intercept treatment dummies are equal to zero (calculated $F = 4.56$, critical $F = 3.35$ at 5% level). Graphically, the line fit tells the story.

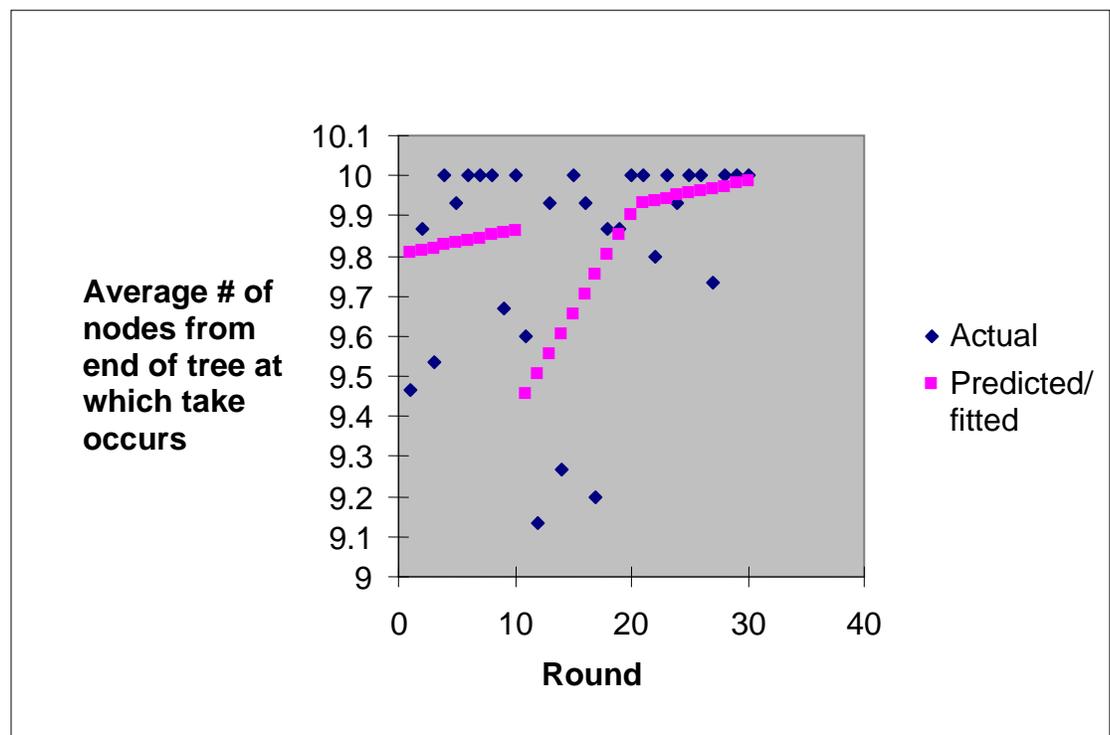


Figure 9. Within-subjects T2-T1-T2 Comparisons

Both statistically and visually it appears that switching from the clock format (rounds 1-10) to the tree format (rounds 11-20) is associated with subjects postponing the act of taking. Furthermore, switching back to the clock format from the tree format is associated with a return to earlier takes (in rounds 21-30). While one might claim that the results from rounds 11 through 30 just illustrate unraveling to the subgame perfect equilibrium (SPE) – and they might – no such explanation can

be made for the sharp break between round 10 and round 11, which if anything illustrates “deconvergence” away from such an equilibrium.

In a further check on the ability of changes in game form to perturb play on a within-subject basis, the T1-T2-T1 session also reveals significant differences in convergence to equilibrium across treatments. Switching from the tree format (rounds 1-10) to the clock format (rounds 11-20) leads to a break in the series, associated with subjects taking much earlier in the clock format. While this could be argued to be evidence of convergence to the SPE (though such an argument would incorrectly ignore the role of the time trend variable in controlling for such convergence) the switch back to the tree format in rounds 21-30 is associated with a break *away* from the SPE (counter to the time trend); this puts to rest the idea that switching formats does not affect play on a within-subjects basis. Statistically the treatments are significant (calculated $F = 12.2151$, critical $F = 3.35$ at 5% level), and graphically the results are as below.

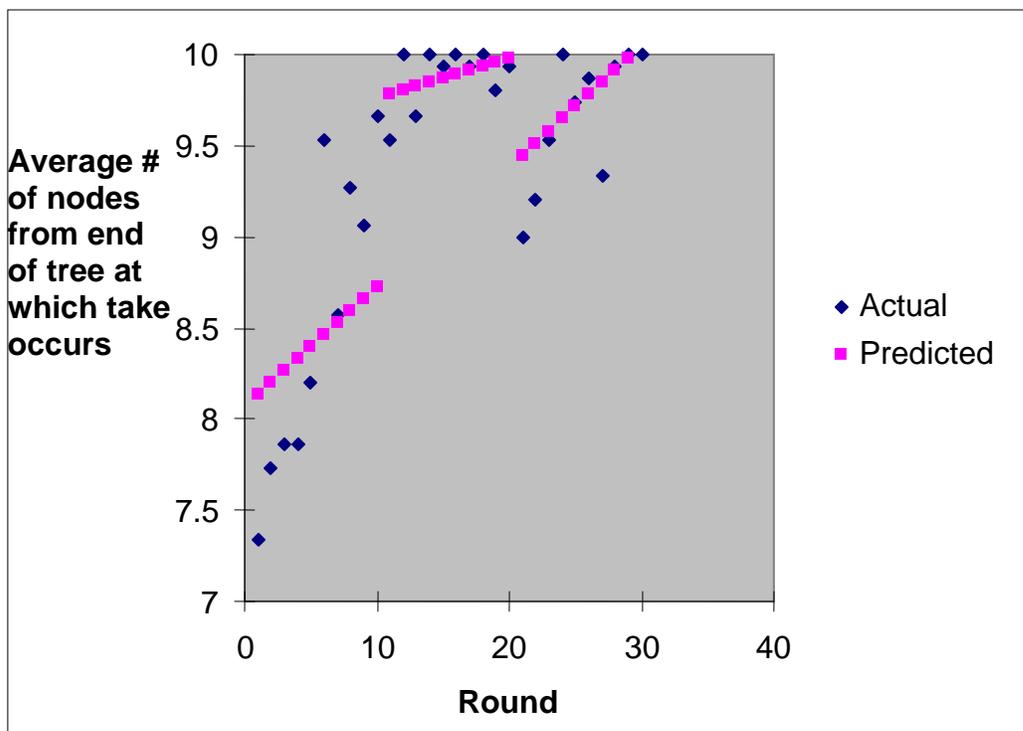


Figure 10. Within-subjects T1-T2-T1 Comparisons

6.3 Simultaneous Dutch Results

Behavior across isomorphic versions of the simultaneous-bid Dutch auction employing different institutional formats is different. Pooling data across all sessions for the same treatment (e.g. all rounds from all parts for T7 from all experiment sessions are analyzed as belonging to one distribution) and performing rank-sum tests to ascertain whether we can reject the hypothesis that the distribution of deviations from theoretical predictions for T8 is the same as that for T7, we find that a rank-sum test rejects that the distributions are indistinguishable (p-value=0.0000).⁷

For the tree format of the simultaneous Dutch auction, we find that the distribution of deviations is significantly different from a distribution of zeroes (p-value=0.0000). Similarly, for the clock format of the simultaneous Dutch auction, the distribution of deviations is significantly different from a distribution of zeroes (p-value=0.0000). Note that the average deviation for T7 is 0.6666, while the average deviation for T8 is 1.2565; thus bidding is higher in T8 than in T7.

Graphically, a time series plot of the average deviation from the theoretical prediction, in each round, for each of T7 and T8, shows both how the results differ across treatments and where they sit relative to the theoretical prediction in each round.

⁷ These tests potentially understate the difference between T7 and T8, for the same reasons given in footnote 5.

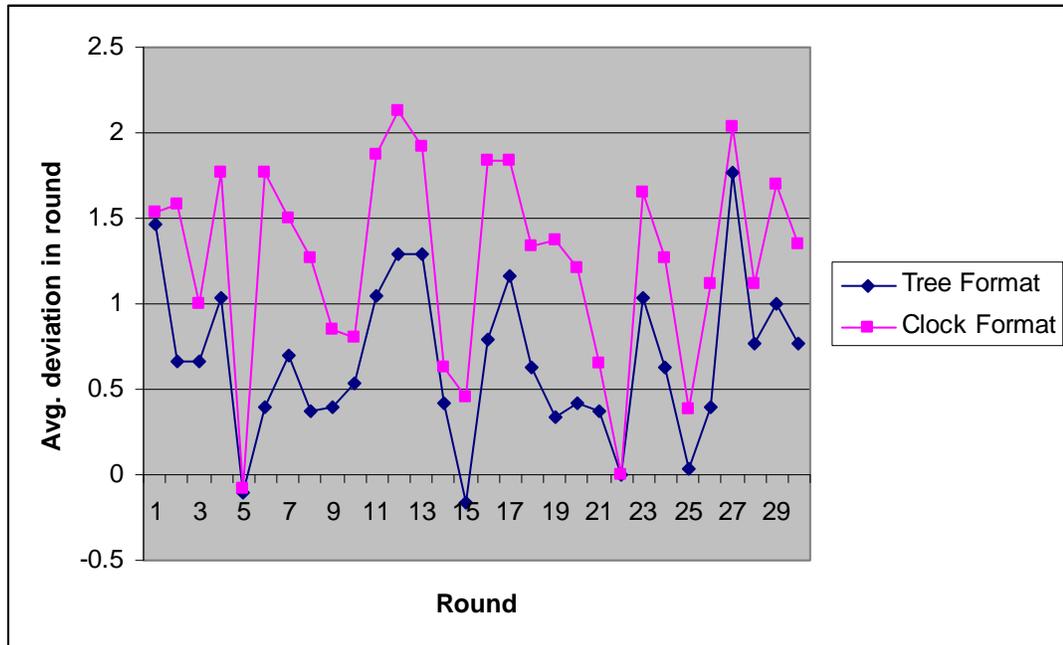


Figure 11. Bid Deviations in Simultaneous-bid Dutch Auctions

6.4 Simultaneous IPV Centipede Results

Behavior differs across institutional formats for the simultaneous-take IPV centipede game. Pooling all data across rounds, parts, and sessions, we find that the rank-sum test rejects the hypothesis that the distribution of deviations from predicted take is the same across treatments (p-value=0.0000).

For the tree format of the simultaneous-take IPV centipede game, we find that the distribution of deviations is significantly different from a distribution of zeroes (p-value=0.0000). In a similar test using data from the clock format of the simultaneous IPV centipede game, we find that the distribution of deviations is significantly different from a distribution of zeroes (p-value=0.0000).

In order to better illustrate the statistical results pertaining to the simultaneous-take IPV centipede game, the following graph plots the time series of the average deviation in “take” from the theoretical prediction for each institutional format.

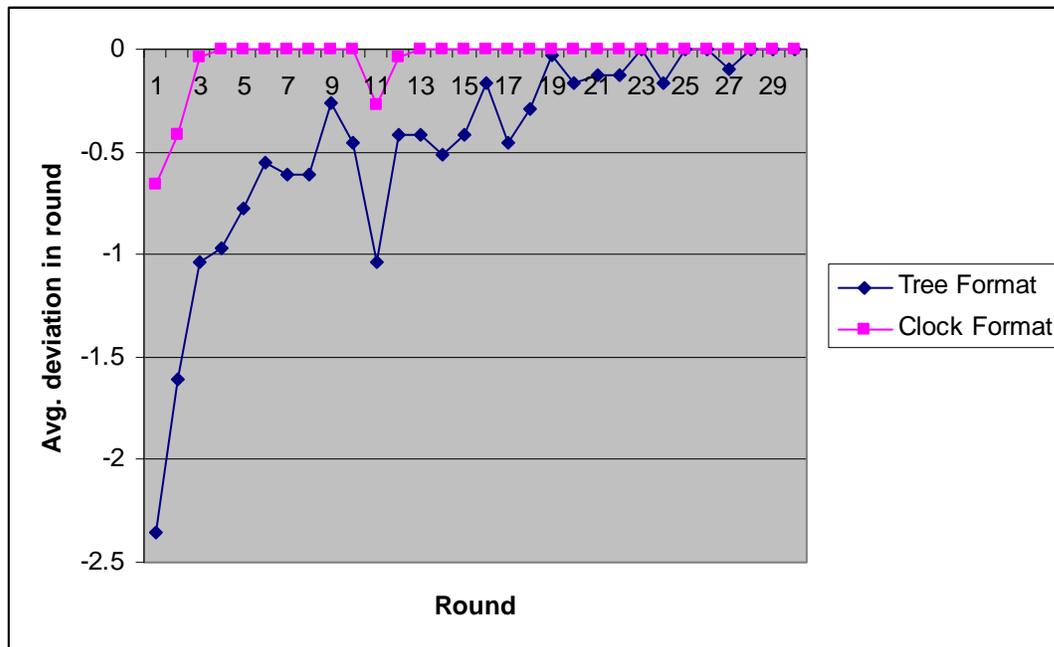


Figure 12. Take Deviations in Simultaneous-move IPV Centipede Games

Note that in individual rounds, starting in the fourth round, perfect unraveling is observed in the clock format of the simultaneous-take IPV centipede game. In fact, from round 4 onward, 25 of 27 rounds exhibit perfect unraveling by every pair of subjects across all pooled sessions of the experiment. This prevalence of unraveling we believe to be unprecedented for two-player centipede games.

6.5 Simultaneous versus Sequential Results: How does Dynamic Structure Matter?

At this point we have established that Institutional Format (IF) is a significant determinant of how people behave in otherwise theoretically-isomorphic games. What about Dynamic Structure (DS)? Might the structure of “who moves when” have an impact on behavior beyond that already captured in a risk neutral Nash Equilibrium model of bidding, or in a subgame perfect equilibrium model of takes in a centipede game? We address this by looking at deviations between actual data

and theoretical predictions across games with *different* Dynamic Structure, but the *same* Institutional Format.

While the bid functions for sequential Dutch and simultaneous Dutch are different, one can put them on a comparable footing by looking at deviations in the data relative to their respective predictions (based on said different bid functions). The prediction across all rounds for both the simultaneous and sequential IPV centipede games is for a take at the first node.

We find that in every comparison – simultaneous Dutch in tree format versus sequential Dutch in tree format (p value = 0.0000), simultaneous IPV centipede in tree format versus sequential IPV centipede in tree format (p value = 0.0000), simultaneous Dutch in clock format versus sequential Dutch in clock format (p value = 0.0000), simultaneous IPV centipede in clock format versus sequential IPV centipede in clock format (p value = 0.0000) – the distributions of deviations from theory are different across simultaneous and sequential structure games. Moreover, the deviations from theory always have the following feature: simultaneous always bids higher (resp., takes earlier) than sequential; this is true across all forms of Dutch auction and centipede games. Graphically, time series plots of deviations make this clear.

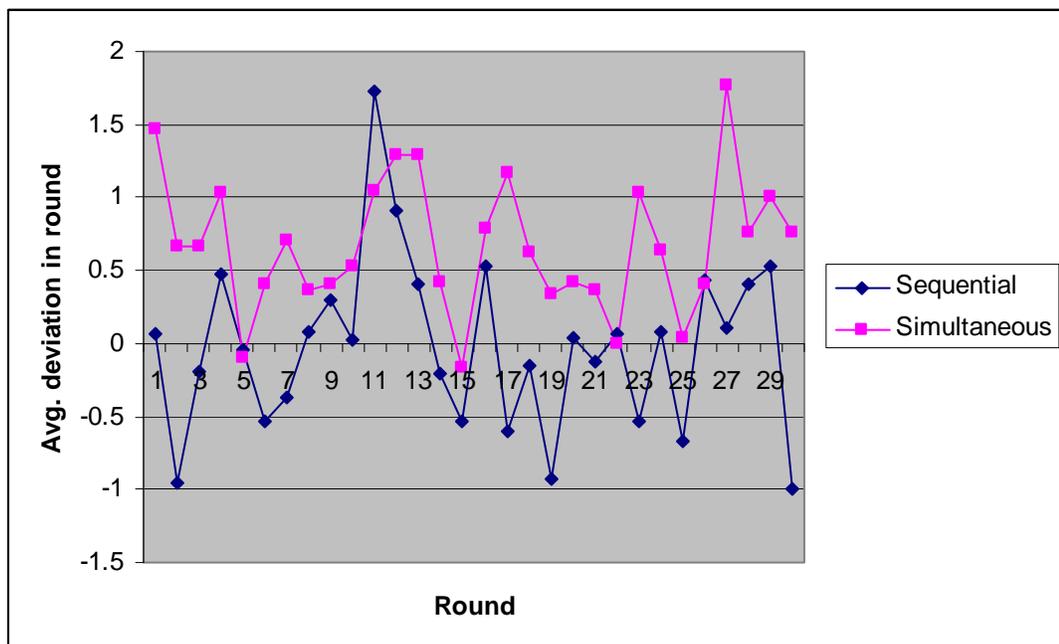


Figure 13. Bid Deviaions in Tree Format Dutch Auctions

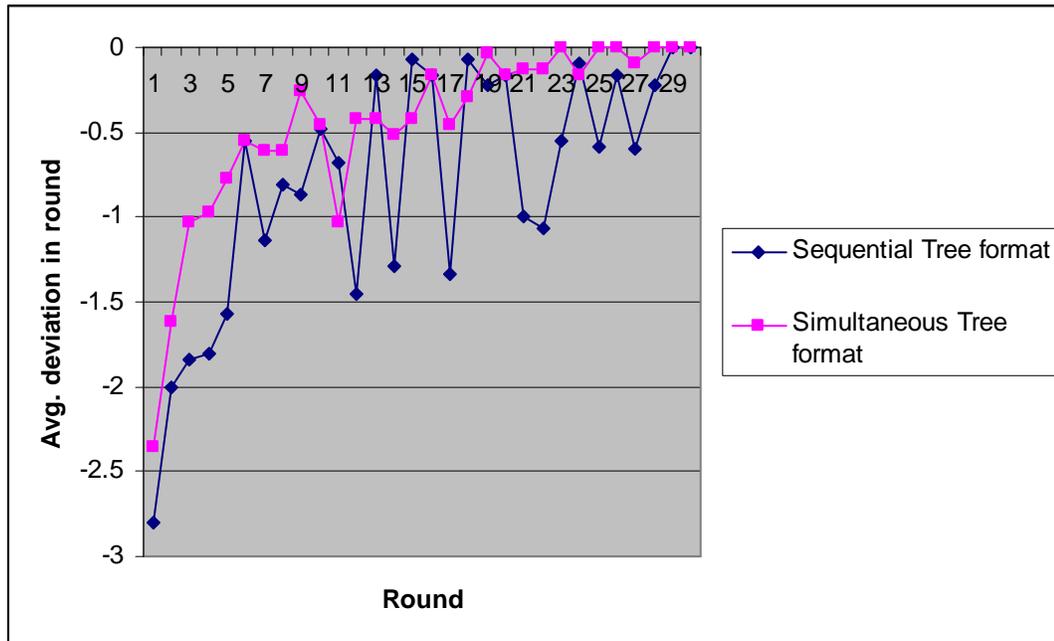


Figure 14. Take Deviations in Tree Format IPV Centipede Games

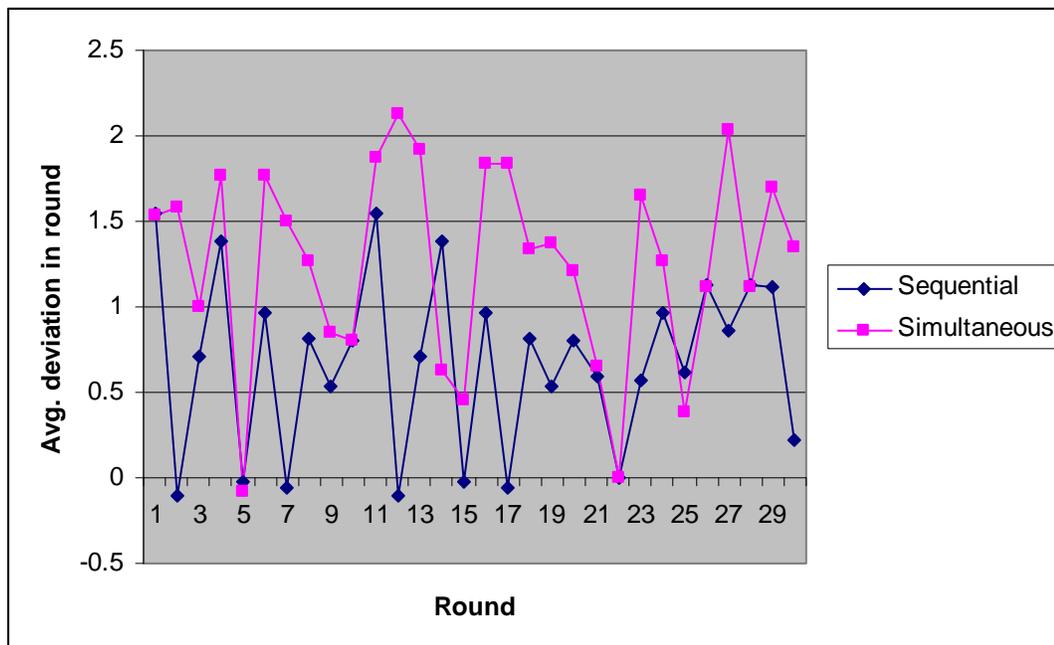


Figure 15. Bid Deviations in Clock Format Dutch Auctions

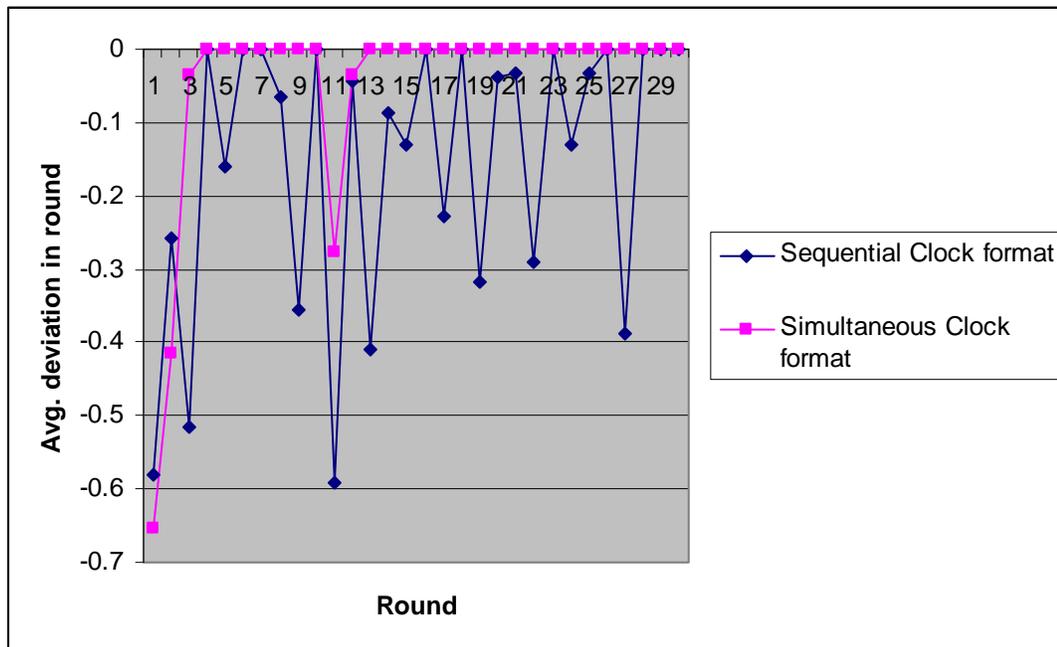


Figure 16. Take Deviations in Clock Format IPV Centipede Games

Note that these results are *not* predicted by theory; the implications of move order for equilibrium are *already* in the bid functions used to make the prediction (resp., subgame perfect equilibrium prediction of a take at the first node). We are instead dealing with something different – something “new”, at least in terms of economists’ awareness of it. Namely, there is something about being “on the clock” at the same time as another player in a real time game that makes people behave differently than when they alternate “exclusive” turns in a real time game. In particular, players in simultaneous versions of a real time game seem less willing to let the game continue; this generalizes across Dutch auctions *and* centipede games.

7. Summary and Conclusions

We get some striking results. Winning bids are consistently higher and successful take nodes consistently earlier with the clock format than with the tree format for four games with

independent private values: sequential-bid Dutch auctions, sequential-take centipede games, simultaneous-bid Dutch auctions, and simultaneous-bid centipede games.

Looking at variations in the centipede game, we find that the rate at which the equilibrium is approached can be controlled by variations in IF and DS. Starting with the sequential-take IPV centipede game in tree format (at one extreme) we find comparatively late unraveling (not unlike findings reported by McKelvey and Palfrey, 1992). But from that baseline we find that changing either the DS to simultaneous-take or the IF to clock format leads to earlier convergence to the unraveling prediction. The convergence to the unraveling outcome is more pronounced with the change in IF than the change in DS. And when we change *both* the IF and DS – arriving then at the simultaneous-take IPV centipede game in clock format – we find extremely rapid convergence to the unraveling equilibrium. It is also notable that we find all of these results with two-player ($n = 2$) games. This is important for two reasons: (a) this pushes back the boundary for which strong unraveling results have been obtained (Rapoport, et al., 2003 and Murphy, et al., 2006 report results for $n = 3$ and $n = 7$) and (b) holding n constant and focusing on (clock and tree) institutional formats has allowed us to generate regularities that generalize across games.

In the Dutch auction, we obtain close to the risk neutral prediction when we use the tree format rather than the traditional clock format. The clock format, on the other hand, yields bids greater than risk neutral theoretical bids. Overall, we get data that more closely resemble theoretical predictions for both Dutch auctions and centipede games when we use the (clock or tree) format that is *not* traditionally associated with that market or game.

The finding that clock games experience earlier takes than tree games is robust to implementations in both sequential and simultaneous dynamic structures, and both centipede games and Dutch auctions. That is to say, clock formats reliably produce earlier takes than tree formats in a manner that generalizes across different types of games (i.e. markets or stylized

game theoretical constructs) and across different structuring (simultaneous or sequential) within these types of games. This result holds across all of our treatments.

What this seems to be telling us is that the institutional format is the primary determinant of what have been accepted empirical properties of both Dutch auctions and centipede games. In that way, these “stylized facts” of the properties of Dutch auctions and centipede games are determined by the clock or tree choice of institutional format in implementation of these games. As such: (a) the behavioral properties of the centipede game are not independent of its traditional implementation in tree format; and (b) the behavioral properties of the Dutch auction are not independent of its traditional implementation in clock format. The institutional formats of these games are essential features that drive real behavior, not mere details of implementation. In this way, we are finding results for centipede games that correspond to long accepted results that the institutional formats of markets are central features that determine their allocation and pricing properties (Smith, 1982; Plott, 1982; Friedman and Ostroy, 1995; Zhan and Friedman, 2007).

Furthermore, we have documented an additional regularity involving dynamic structure. Specifically, in all four of our real time games, simultaneous-move structure leads to earlier takes than sequential-move structure. This is readily apparent for the centipede game (as the equilibrium is the same in all rounds of all implementations), but is also (if less obviously) true for the Dutch auction. In the Dutch auction, we find that the deviations from the risk neutral Nash equilibrium predictions are greater for the simultaneous-bid auction than the sequential-bid auction. In addition, in a number of rounds we find that winning bids in the simultaneous-bid Dutch auction are higher than winning bids in the sequential-bid Dutch auction in absolute terms as well. This is particularly striking given that (with our parameterization) the bid functions are such that the simultaneous-bid Dutch auction should never yield higher prices than the sequential-bid Dutch auction.

Overall we find that what might be considered fairly subtle aspects of the received way of implementing games in real time do in fact have quite powerful effects. The fact that they had

been sitting in the background, bundled into canonical institutions or games, does not mean they were not always affecting behavior. And the fact that we now know they are there should help all researchers in designing institutions and analyzing data generated therein. In future research we aim to search for other such effects, and to shed light on their functioning.

References

- Aumann, Robert J. (1995), "Backward Induction and Common Knowledge of Rationality," *Games and Economic Behavior*, 8, 6-19.
- Cassady, Ralph (1967), *Auctions and Auctioneering*. University of California Press, Los Angeles.
- Chwe, Michael S.-Y. (1988), "The Discrete Bid Function," *Economics Letters*, 31, 303-306.
- Cox, James C., Bruce Roberson, and Vernon L. Smith (1982), "Theory and Behavior of Single Object Auctions," in V.L. Smith (ed.), *Research in Experimental Economics*, vol. 2. JAI Press, Greenwich.
- Cox, James C., Vernon L. Smith, and James M. Walker (1983), "A Test that Discriminates Between Two Models of the Dutch-First Auction Nonisomorphism," *Journal of Economic Behavior and Organization*, 4.
- Friedman, Daniel and Joseph Ostroy, (1995), "Competitiveness in Auction Markets: An Experimental and Theoretical Investigation," *Economic Journal*, 105(1), 22-53.
- Katok, Elena and Anthony M. Kwasnica (2008), "Time is Money: The Effect of Clock Speed on Seller's Revenue in Dutch Auctions," *Experimental Economics*, 11(4), 344-357.
- Lucking-Reilly, David (1999), "Using Field Experiments to Test Equivalence of Auction Formats: Magic on the Internet," *American Economic Review*, 89(5), 1063-1080.
- McKelvey, Richard and Thomas R. Palfrey (1992), "An Experimental Study of the Centipede Game," *Econometrica*, 60, 803-836.
- McKelvey, Richard and Thomas R. Palfrey (1998), "Quantal Response Equilibria for Extensive Form Games," *Experimental Economics*, 1, 9-41.
- Murphy, Ryan O., Amnon Rapoport, and James E. Parco (2006), "Breakdown of Cooperation in Iterative Real-Time Trust Dilemmas," *Experimental Economics*, 9, 147-166.

Plott, Charles R., (1982), "Industrial Organization Theory and Experimental Economics," *Journal of Economic Literature*, 20(4), 1485-1527.

Rapoport, Amnon, William E. Stein, James Parco, and Thomas E. Nicholas (2003), "Equilibrium Play and Adaptive Learning in a Three Person Centipede Game," *Games and Economic Behavior*, 43, 239-265.

Smith, Vernon L. (1982), "Microeconomic Systems as an Experimental Science," *American Economic Review*, 72(5), 923-955.

Turocy, Theodore L., Elizabeth Watson, and Raymond C. Battalio (2007), "Framing the First-price Auction," *Experimental Economics*, 10, 37-51.

Vickrey, William (1961), "Counterspeculation, Auctions, and Competitive Sealed Tenders," *Journal of Finance*, 16, 8-37.

Zauner, K.G. (1999), "A Payoff Uncertainty Explanation of Results in Experimental Centipede Games," *Games and Economic Behavior*, 26, 157-185.

Zhan, Wenjie and Daniel Friedman (2007), "Markups in Double Auction Markets," *Journal of Economic Dynamics and Control*, 31(9), 2984-3005.