# Stability in Competition? Hotelling in Continuous Time

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*We study Hotelling's classic duopoly location model in continuous time with flow payoffs accumulated over time and the price dimension made explicit. In an experimental setting, subjects chose price and location in treatments varying only by the speed of adjustment. We find that the principle of minimum differentiation generally holds, with little distance between subjects' location decisions. Price decisions, however, tend to be volatile, which is arguably consistent with theory. Our data also support recent literature that the ability to respond quickly increases cooperation.*

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Hotelling's seminal paper *Stability in Competition* (1929) characterized the stylized fact that individuals buy commodities from different sellers despite modest differences in price, and the work continues to garner citations at an impressive pace even 85 years after its publication. The model is often taught and discussed as a simple location model in which firms decide how to position their product in a linear product space. This space is generally taken to be location, although the model has been adapted extensively to numerous phenomena ranging from industrial organization to politics.

In the classic setup, firms face a constant price and a uniformly distributed mass

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of potential consumers that will buy at most one unit from one of the firms as determined by a specified utility function. Consumer utility is decreasing linearly in distance, and as such consumers will purchase the homogenous good from the closest vendor. With two firms in the market, this results in the firms locating adjacent to each other at the midpoint; this is to say, the firms produce identical products. This is known as the *principle of minimum differentiation.*

However, Hotelling suggested but did not prove that this spatial competition would lead to a price equilibrium between firms. This has since been proven to be incorrect for his specification of the model with linear transportation costs, as firms can always improve profits by moving to a new position after a competitor's move, be it a new location or a new price point. The absence of a pure strategy Nash equilibrium contrasts starkly with the "folk wisdom" that firms minimize the distance between one another and thereby maximize payoffs.

This contrast between formal theory and folk wisdom motivates our empirical work. With theoretical work unable to provide a clear equilibrium on such an entrenched model, we turn to the lab to test the predictions that Hotelling attempted to elucidate. We adhere closely to the original model and question whether Hotelling's Law — another name for the principle of minimum differentiation — holds. We also test whether the ability to rapidly adjust location and price can induce firms to cooperate to achieve higher profits. In a continuous time setting in the laboratory, we examine variants of the Hotelling model in which pairs of anonymously matched subjects can adjust their price and location during four-minute periods. Treatments vary in how often they are allowed to adjust their position, ranging from free adjustment on either dimension to being limited to adjustment on only one dimension during set blocks of time. Subjects accrue flow payoffs throughout the period that depend simply on their location and price positions relative to their counterparts in that moment in time. Subjects are randomly rematched after each period, with sessions lasting 12 periods.

Our results indicate that despite theoretical ambiguity suggesting otherwise, Hotelling's principle of minimum differentiation largely holds. We also demonstrate that free and unlimited adjustment leads to higher payoffs for subjects, while limiting adjustment lowers prices and payoffs and increases competitive behavior. We provide circumstantial evidence that collusion arises from signaling from one of the subject pairs, either through momentary jumps to desired positions or willful loss in payoffs while waiting for a counterpart to fall in line. However, non-competitive behavior is not widely observed, and it is clear that the Hotelling model is not one that leads easily to a settled state. As such it should only be used very cautiously when explaining duopolies, whether they are political parties competing for voters or ice cream push-carts on a beach.

Section 1 provides background on Hotelling's seminal model and its theoretical development, and Section 2 recalls his original notation. Section 3 details the experimental design, Section 4 gives the results of the experiment, and Section 5 concludes.

## I. Background

It is appropriate to distinguish between horizontal and vertical differentiation. With horizontal differentiation, not all consumers will agree on which firm or product is preferred. With fixed prices, Hotelling's model only discusses horizontal differentiation in the form of a location choice by the firm. Despite most colloquial discussion leaving the analysis there, Hotelling actually included prices and devoted a significant portion of his paper to discussing vertical differentiation. With vertical differentiation, all consumers will agree which product is preferred, all else held constant. The dimension is taken to be be price for the purposes of this discussion, although it could also be product quality with prices held constant.

### A. Evolution of Hotelling's Original Model

The original model has been appropriated to attempt to explain a wide range of phenomena, concentrated most densely in the political science and industrial organization literatures. These applications range from voting habits (Downs, 1957) to entry deterrence (Schmalensee, 1978) to competition in specific industries (Baum and Mezias, 1992 for hotels, Calem and Rizzo, 1995 for hospitals, and Iyer et al., 2014 for religions, as examples).

Unfortunately, however, many of these applications do not take into account how sensitive the Hotelling location model is to small changes to the setup and set of assumptions. Eaton and Lipsey (1975) detail equilibria for more than two players, and show that minimum differentiation does not generalize easily even if local clustering tends to emerge. With four players, for example, the equilibrium has two players on each of the first and third quartiles. With three players, however, there is no way to satisfy the pure equilibrium conditions (Shaked, 1982). Salop (1979) changed the linear city to a circle — among other alterations — which results in maximum differentiation in product space, such that firms are evenly distributed around the circle.

Perhaps most significantly, D'Aspremont et al. (1979) show that the principle of minimum differentiation does not hold due to the non-existence of a price equilibrium when firms are not sufficiently far from each other. This is because demand is discontinuous when firms are located close together. They propose a simple modification to the consumer utility function — quadratic instead of linear transport costs — that restores the continuity of demand and allows for a price equilibrium anywhere. However, this changes the sign of the derivative of the firms' profit functions with respect to location from positive to negative; this is to say, firms then locate as far from each other as possible.

This prompted a number of authors to implement alterations to the model to remedy this equilibrium non-existence problem. Graitson (1980) assumes "max-imin" behavior, in which a firm that is too close to an opponent sets a price that maximizes its profit function taking the other firm's price to be zero. This leads to a "maximin equilibrium" which gives an equilibrium with firms located at the first and third quartiles charging Nash-Cournot prices. Neven (1985) integrated the D'Aspremont et al. suggestion of quadratic transport costs and gave the model two stages, where firms first engage in horizontal differentiation before choosing a price.[1] He shows that a pure strategy price equilibrium exists for every pair of products, and confirms that firms maximize horizontal differentiation in equilibrium.

Generally, subsequent work — Cremer et al. (1991) and Irmen and Thisse (1998), for example — followed the quadratic transport costs approach, although Economides (1986) examined a range of utility costs of transportation and showed that not all specifications resulted in maximal differentiation. However, the problem of equilibrium existence within Hotelling's original setup lingered, and increasingly nuanced approaches attempted to tackle the problem.[2] Close relatives of the Hotelling model — such as Shaked and Sutton (1982) — give the model an entry decision stage or alter the dimensions on which firms compete. More modern work has seemingly strayed even further from the original setup to attempt to capture real world phenomena, particularly in the IO literature. We cannot even begin on an exhaustive list here, as the original paper had over 8000 listed citations at the time of writing. Two things are clear from the existing literature, however. First, the predictions of the model are sensitive to small changes to the setup. Second, the model has defied many efforts to cleanly characterize its equilibrium, with the possibility of a pure-strategies equilibrium having been been definitively eliminated.

But despite the result-altering breakthroughs, Hotelling's conclusions are still widely cited — if only casually — with the equilibrium difficulties frequently ig-

[1]Hotelling himself hinted at a two stage approach when prices were decision variables, for the reason that prices are easier to adjust than locations or product variety. Other papers — such as Graitson (1980) and Economides (1984) — tacitly followed this approach.

[2]See Gabszewicz and Thisse (1986) for an early overview and Caplin and Nalebuff (1991) for an approach that gives the additional assumptions and conditions needed for a pure strategy price equilibrium.

nored. This paper explores the applicability of his original result as well as the robustness of the more nuanced conclusions of subsequent models in an experimental setting.

### B. Previous Experimental Work

There have been a number of attempts to test the Hotelling model in an experimental setting. Brown-Kruse and Schenk (2000) — along with its predecessor, Brown-Kruse et al. (1993) — investigate a two-player uncertain endpoint model, but focus on the effect of communication on collusion. They find that communication led participants to locate near the quartiles to maximize joint profit, but the principle of minimum differentiation did seem to hold in their results when communication was limited. Huck et al. (2002) were the first to test a four-person Hotelling game, but found little support for the equilibrium hypothesis. Kephart (2014) showed that the four-player Nash equilibrium emerged more quickly with the ability to adjust location instantly.[3]

Very few authors have included vertical differentiation in an experimental setting. This could be due to the equilibrium existence problems discussed above, or due to a lack of technological capability. To our knowledge, only three works have tested a game with price as a choice variable in addition to location. The first attempt was by Mangani and Patelli (2002), who specified their model with quadratic transport costs such that theory would suggest subjects should maximally differentiate in the location dimension to relax price competition. The authors tested this with three treatments: a two-stage location then price game mirroring Neven's setup, a treatment with only periodic location adjustments, and a treatment in which price and location were chosen in the same period. The one-shot game in the last of these treatments does not have a theoretical benchmark. Subjects, however, tended toward the center of the location space, although were still 20-30 percent of the action space away from their counterparts,

[3]The four-player location-only game has its own form of the principle minimum differentiation as the equilibrium, with players located back-to-back on the first and third quartiles.

on average. The authors suggested — but did not directly test — risk aversion as an explanation, although their conclusions are weakened by a within-subject design.

Kusztelak (2011) allowed limited communication between subjects as well as also including quadratic transport costs. In his first treatment, prices were automatically computed, reducing the game to a location-only decision with 101 discrete location fields (between 0 and 100). Subjects behaved as expected with maximal differentiation in this treatment. But when a price decision was added in the second treatment, the differentiation decreased significantly, with over 40 percent of location in the center of the action space. He hypothesizes that increased model complexity reduces differentiation, and also tests a market with two horizontal decision variables along with the price decision variable in the final treatment.

Finally, Barreda et al. (2011) attempted to test the hypothesis that firms use product differentiation to relax price competition by focusing on a limited, discrete location decision. Specifically, subjects could only choose among either seven or eight location slots, depending on the treatment. In their most relevant treatments, the authors found less product differentiation than theory would predict, and relatively few high prices.

### *C. Our Contribution*

Our work contributes to the literature in several important ways. First, this experiment is the cleanest test to date of a two-player Hotelling model with horizontal and vertical decision variables and linear transport costs, thus giving a better view into how Hotelling's seminal result fairs in an ideal setting. Second, this experiment is the first to test the model in continuous time. Our work also takes a novel approach by blurring the sharp distinction between the continuous choice model and sequential models, providing insight on how the model should be applied and the effect the ability to adjust quickly affects firms behavior. Finally, superior lab software and programming gives participants a more intuitive interface and faster learning experience to allay concerns of participant apprehension skewing results in the competitive setting.

## II. Model and Predictions

First, we begin by recalling Hotelling's assumptions and notation. There are customers evenly distributed on a line of length $l$, with firms $A$ and $B$ selling a homogenous product with zero production cost.[4] Each customer consumes one unit of the good, and will buy from the seller who gives the least delivered price. Firms locate at points $a$ and $b$ respectively, such that $a$ is the distance from 0, $b$ is the distance from $l$, $a + b \leq l$, and $a \geq 0$,$b \geq 0$. Firms also set prices $p_A$ and $p_B$, respectively. Transport costs are linear and are denoted by $c$. For simplicity, we normalize $l$ and $c$ to be 1 in our experiment.

First, consider the case that price and location are chosen simultaneously. Payoff functions for $A$ and $B$ are given by:

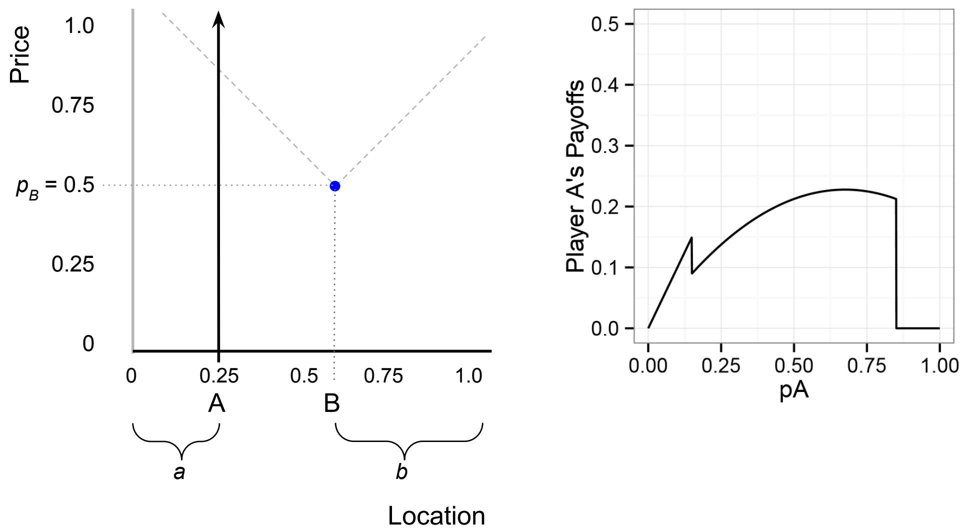
$$\pi_A(p_A, p_B, a, b) = \begin{cases} ap_A + \frac{1}{2}(l-a-b)p_A + \frac{1}{2c}p_Ap_B - \frac{1}{2}p_A^2 & \text{if } |p_A - p_B| \leq c(l-a-b) \\ lp_A & \text{if } p_A < p_B - c(l-a-b) \\ 0 & \text{if } p_A > p_B + c(l-a-b) \end{cases}$$

$$\pi_B(p_A, p_B, a, b) = \begin{cases} bp_B + \frac{1}{2}(l-a-b)p_B + \frac{1}{2c}p_Ap_B - \frac{1}{2}p_B^2 & \text{if } |p_A - p_B| \leq c(l-a-b) \\ lp_B & \text{if } p_B < p_A - c(l-a-b) \\ 0 & \text{if } p_B > p_A + c(l-a-b) \end{cases}$$

The profit function of Player A is illustrated in Figure II.1, with $l = c = 1$, player A located at $a = 0.25$, player B at $0.6 \Rightarrow b = (1 - 0.6) = 0.4$, with a fixed price of $p_B = 0.5$, and varying $p_A$ from zero to one. As player A increases $p_A$ they transition from controlling the entire territory ($p_A \in [0, 0.15)$), to possessing a

[4] This experiment only examines the two-player game, but can be generalized to $n$ sellers. See Brenner (2005) for a derivation of the model with more than two players.

Figure II.1. : Payoff Function Diagram




portion of the market jointly with B ($p_A \in [0.15, 0.85]$), and finally to possessing no market share ($p_A \in (0.85, 1]$). Player profit functions are discontinuous at the points where the delivered price of one firm is equal to the price of a rival at the rival's location.

Figure 1 in D'Aspremont et al. showed that there is a Nash-Cournot equilibrium point only if sellers are sufficiently far from each other, or such that:

(II.1)
$$\left(l + \frac{a-b}{3}\right)^2 \geq \frac{4}{3}(a+2b)l$$

(II.2)
$$\left(l + \frac{b-a}{3}\right)^2 \geq \frac{4}{3}(b+2a)l$$

When sellers locate close to one another, it is optimal for them to undercut each other and capture the entire market. But if (1) and (2) hold, then both $\partial\pi_A/\partial a$ and $\partial\pi_B/\partial b$ are strictly positive, implying each firm should move closer to her rival. Once the firms are relatively close to one another, (1) and (2) are violated, implying a Nash equilibrium does not exist.[5] Therefore, subjects in the experiment have an incentive to push toward the center, then try to undercut each other in the price dimension to grab the entire market. This prediction would see subjects follow each other closely in the action space, with frequent adjustment to price and location and large volatility in profits.

A possible evasion of this problem is to assume the maximin strategy introduced by Graitson (1980). Here, the seller charges the profit maximizing price if she is likely to be undercut by her competitor when charging the Nash-Cournot price, and the Nash equilibrium price if not. Graitson proves that a socially optimal equilibrium — i.e. one that minimizes transport costs — exists with this strategy in which firms charge Nash-Cournot prices and locate at the first and third quartiles.[6]

In the two-stage game, firms first simultaneously choose location, then simultaneously choose a price with full information from the first stage. Apart from this feature, the setup is the same as above. Dasgupta and Maskin (1986) prove that each price-setting stage has an equilibrium in mixed strategies and Osborne and Pitchik (1987) examine the equilibrium that results from firms using mixed strategies in this stage. They characterize — but are unable to prove the existence of — a unique perfect equilibrium in the first stage in which each firm locates 0.27 from the endpoints of the unit interval, which is clearly quite close to the equilibrium that arises from minimax behavior. In the price-setting stage, for a symmetric location pair, the equilibrium price strategy is a union of two intervals — such that the CDF will be kinked. Prices then fall between .5 and 1, with most of the probability weight falling on price of 1. This prediction would see participants in the experiment at or near the profit maximizing positions.

In both versions, players can gain higher profits from collusion, but have incentive to cheat. This mirrors the classic Prisoner's Dilemma, albeit with far more

[5]It is worth noting that there is a trivial Nash equilibrium at $p_A^* = p_A^* = 0$ if $a = b$. This follows from Bertrand competition, in which there always exists an equilibrium uniquely determined by zero prices.

[6]Similar to Graitson, Tabuchi (1994) purposes that firms will maximize on one dimension and minimize on the other in the two-stage game.

intermediate outcomes. Friedman and Oprea (2012) showed that continuous time treatments greatly increase cooperation; as such, we would predict successful non-competitive behavior to be much more prevalent in continuous time treatments.

With the uncertainties in the equilibrium conditions in mind, we turn to the laboratory to answer lingering questions about the results and behavior of firms in Hotelling's classic model of competition.

## III. Experimental Design

The experiment was performed in sessions differing only in the timing of the game. We study three treatments: *Discrete*, *Continuous Instant*, and *Continuous Slow*. Sessions included of just one of the treatments, and consisted of two practice periods followed by 12 potentially paid periods. Subjects were randomly matched into two-person pairs, and rematched with a new counterpart each period. Periods lasted 4-5 minutes with random endings for subject pairs to avoid endgame effects, although practice periods lasted for 30 seconds. Sessions contained six participants, and subjects could be re-matched to any other subject at the start of another period.[7] Note that for all treatments, there was no difference between counterparts in any of the game's parameters. In all treatments, participants choose their location and price by clicking in the x-y action space.

In all treatments participants choose their location and price by clicking in the x-y action space. Action selections could be made with pixel precision. In some previous laboratory investigations action selection grids have been limited from the single digits to several dozen discrete actions available. Our implementation - with several hundred thousand available x-y coordinates available to participants[8] - approximates continuous action selection far more closely.

In the *Discrete* treatment, subjects played an n-stage game in which location

[7] In some pilot sessions, we had eight-subject sessions that were divided into four-subject silos. While subjective, we felt that groups of this size could be risky in terms of subjects being able to identify a counterpart they had previously been paired with, potentially altering behavior.

[8] We implement an action space that is 425 pixels square, resulting in about 180,000 potential location and price combinations available to subjects

is selected first, followed by price with full information about location decisions. Subjects were given 3 seconds to choose their location, indicated by a progress bar on the top of their computer screen. The screen then adjusts to reflect the location the subject and her counterpart have chosen, and subjects were given 3 seconds to choose price, again indicated by a progress bar. We define these 3 second intervals as subperiods. Subjects had four subperiods of price decisions before they were allowed to readjust location.[9] Figure III.1b gives a screenshot of the user interface for this treatment. "Flow" payoffs are shown as bars in the graph on the right, and are updated after every subperiod. The blue dot indicates the subject's position in the last subperiod, while the green dot indicates her counterpart's position. The black line shows the subject's current choice for that subperiod, while the grey line simply follows the mouse.

In the *Continuous Instant* treatment, subjects chose both location and price freely and instantaneously.[10] A screenshot of this treatment is shown in Figure III.1a. Flow payoffs are shown in the graph on the right, and are updated continuously. The blue dot indicates the subject's current position, and the pink dot shows her counterpart's current position. The grey crosshairs simply follow the mouse.

The *Continuous Slow* treatment is identical to the previous treatment except for a "speed limit" on subject movement in action space. When a subject chooses a new location and price coordinate, a grey dot appears at that location while her actual position adjusts slowly to that point. If a subject wants to change direction while her position is adjusting, a new grey dot appears and her position immediately begins to adjust to the new target. As an analogue to the discrete time treatment, subject position could be adjusted four times quicker on the price dimension than on the location dimension.

[9]In pilot sessions, we also ran treatments in which location- and price-setting subperiods alternated, with no discernible difference in subject behavior.

[10]The latency between a subject's click and seeing the action on the computer screen is around 50 milliseconds, or far faster than human reaction time. This latency did increase slightly during periods of very frequent position adjustment by subjects, but not above tolerable levels that would disrupt subject behavior.

In all treatments, subjects were given information about their current payoffs. The user interface included the linear transport costs running away from their position, the cutoff that determined the edge of the area they control, and a shaded region showing the area they control.

Subjects in all sessions were randomly selected using online recruiting software, Greiner (2004), at the University of California, Santa Cruz from our pool of volunteers, who are primarily undergraduates from all major disciplines. All were inexperienced, i.e., had never participated in a Hotelling experiment in our lab. Written instructions given for each treatment are included in the web appendix[11], and these instructions were also read out loud. Following this, subjects saw a short, silent instructional video with on-screen text, which was read aloud as it appeared.[12] Pink noise — a full-frequency audio process that can be used to mask ambient noises — was played in the background to prevent subjects from hearing the mouse clicking of other subjects. Sessions lasted 80-90 minutes each, and subjects were paid their point total multiplied by $20 for two periods, which were decided by an overt dice roll by one of the participants. Following both pilot and paid sessions, we noticed only small differences in subject behavior between *Continuous Instant* and *Continuous Slow* treatments. Therefore, we follow the advice of List et al. (2010) and substitute one discrete time session for one continuous slow session. Average earnings were $16.21, and breakdown by treatment is available in Table 1 .

## IV. Results

### *A. Subject Price and Location Decisions*

To provide an overview of the results, Figure IV.1 gives heat maps of all players' price and location decisions by treatment, respectively. In these figures, "hotter" colors mean players spent more time in these positions, while "cooler" colors in-

[11]The web appendix is at `www.cazaar.com/home/research`
[12]Instruction videos are also available at the web appendix.

Table 1—: Subjects and Payouts by Treatment

| Treatment | Number of Subjects | Average Payout |
|---|---|---|
| Continuous Instant | 24 | $18.39 |
| Continuous Slow | 24 | $14.67 |
| Discrete | 24 | $16.71 |
| Total | 72 | $16.59 |

*Notes*: "Average Payout" includes the $5 show-up fee.

dicate little time was spent in that area of the action space. The most striking feature of these figures is the heat distribution between continuous and discrete time treatments. Subject positions were clearly more concentrated in continuous time treatments, with discrete time positions more evenly distributed in the action space. In continuous time, players tended to be centrally located on the x-dimension, while price positions varied more by treatment. Prices in *Continuous Instant* treatments tended to be the highest of any treatment, with a strong concentration around the highest possible price. Putting a speed limit on adjustment lowered prices and diminished the congregation around the highest prices.

Table 2—: Summary Statistics, by Treatment

| | Discrete | | Continuous Slow | | Continuous Instant | |
|---|---|---|---|---|---|---|
| | Mean | Median | Mean | Median | Mean | Median |
| Price | 0.5787 | 0.606 | 0.5117 | 0.492 | 0.5855 | 0.597 |
| | (0.0184) | (0.0247) | (0.0070) | (0.0096) | (0.0062) | (0.0090) |
| Profit | 0.2534 | 0.2325 | 0.2380 | 0.1980 | 0.2729 | 0.2550 |
| | (0.0096) | (0.0141) | (0.0041) | (0.0058) | (0.0037) | (0.0059) |

*Notes*: Means and block bootstrapped standard errors of prices and profits by treatment. Joint profit maximizing would lead to prices equal to 1 and profits equal to 0.5.

Table 2 gives basic summary statistics by treatment. In the *Continuous Instant* treatment, subjects had the highest average prices and profits of any treatment. When subjects can adjust price quickly but not location, prices were lower than with instant adjustment, and median payoffs were the lowest of any treatment. For comparison, if both subjects exhibited joint profit maximizing behavior, prices would be one and profits would be equal to 0.5 for each subject in the pair.

While the straightforward summary statistics show relatively little difference between treatments, examining within subject pairs tells a different story. Table 3 gives summary statistics on mean and median distance from a subject's counterpart, with "distance" specified as purely location, purely price, and euclidean distances. Note that both axes are scaled to one, so that a distance of .1 is very

Table 3—: Comparison to Counterpart Statistics by Treatment

| | Discrete | Continuous Slow | Continuous Instant |
|---|---|---|---|
| Location Distance (distance on x-axis from counterpart) | | | |
| Mean | 0.2529 | 0.1288 | 0.1578 |
| | (0.0093) | (0.0022) | (0.0021) |
| Median | 0.205 | 0.0875 | 0.1020 |
| | (0.0125) | (0.0019) | (0.0029) |
| Price Distance (distance on y-axis from counterpart) | | | |
| Mean | 0.1714 | 0.1140 | 0.1097 |
| | (0.0046) | (0.0016) | (0.0016) |
| Median | 0.109 | 0.074 | 0.062 |
| | (0.0052) | (0.0013) | (0.0015) |
| Euclidean Distance (from counterpart) | | | |
| Mean | 0.3433 | 0.1921 | 0.2122 |
| | (0.0086) | (0.0024) | (0.0026) |
| Median | 0.3097 | 0.1534 | 0.1615 |
| | (0.01) | (0.0025) | (0.0035) |

*Notes:* Mean and median distances on specified dimension by treatment. Block bootstrapped standard errors in parentheses. Axes are scaled such that maximum differentiation on one dimension would give a distance of one.

close while a distance of .5 is quite far from a counterpart. Subjects were much closer together on all measures of distance in the continuous treatments, such that the discrete stage game tended to push subjects apart in the action space. This can be seen easily in the heat maps discussed above. Price distance is consistently lower across treatments, even in the Continuous Time treatment that did not inhibit location adjustment in any way. Note that the median distances are consistently smaller than the mean distances. Observationally, this is due to some subjects consistently moving away from their counterpart to attempt to avoid the intense competition that characterized many subject pairs. This can be seen particularly clearly in the Continuous Instant treatment, where the median distance between counterparts in the price dimension is just six percent of the action space.

We have documented where subjects tended to locate in both dimensions, but we also wanted to characterize their movement when they did make adjustments. For this, we present in Figure IV.2 a form of an empirical vector field in which average subject movement from a given position is shown. Here, vectors show the average direction that subjects moved starting from that neighborhood. In the background, colors map to the percentage of observations in that neighborhood for which players changed their action set. Darker colors indicate that subjects tended to change their price/location decision in that area more often, with the direction of the change following the overlaid vector, on average.

Subject adjustments vary greatly by treatment. In the *Discrete* treatment, subjects tend to decrease high prices and raise low prices, and tended to change their actions no matter where they were positioned. Beyond this, however, behavior is somewhat erratic. Movement in the *Continuous Slow* treatment is a bit more clear, with subjects tending to adjust towards the center. The heatmap for *Continuous Slow* is a bit deceptive, since action changes were rate limited by the "slow" speed limit. The heatmap for this treatment shows changes in players *target* location and prices, which were far less frequent than in either *Discrete* or

*Continuous Instant* treatments. But the clearest story emerges from the *Continuous Instant* treatment. Here, the lower edges of the figure are darker as subjects made more frequent adjustments to avoid being "boxed in" by a counterpart. Prices tended to be adjusted upwards until about 0.6 — which was the median in this treatment — and downward above that. Central locations with medium to high prices tended to be the most stable action sets.

### B. *Non-competitive Behavior*

As detailed previously, subjects have an ever-present incentive to undercut on either dimension. Thus, it may come as somewhat of a surprise that we see mean and median price decisions between 0.5 and 0.6. We compile non-competitive behavior rates for player pairs. Informally, non-competitive behavior is a situation where two players are able to settle into relatively stable and jointly profitable positions. To capture this sense, for our analysis we define $\rho_{ik}$ as the fraction of time player pair $i$ maintain jointly positive profits within 20 percent of each other — and by implication refrain from undercutting one another — in session $k$. Thus, we will define non-competitive behavior as a situation where two players are able to settle into relatively stable positions. Although these are conservative and arbitrary thresholds, our results are robust to a range of changes to this threshold.

Table A1 shows mean and median non-competitive behavior rates by treatment for the two thresholds for the last six periods of sessions.[13] The continuous time treatments were clearly more conducive to non-competitive behavior than the discrete time treatment, with rates exceeding a quarter of the period on average. Note again that median values were generally well below mean values. This is because some subject pairs were able to quickly come to an agreeable state — thus spending large portions of periods in cooperation — while others could only manage short-lived tacit agreements, or none at all. As one might expect, non-

[13]Despite having two practice periods, we focus on settled behavior here to avoid any learning effects from the opening periods. The results from all periods are shown in Table A1 in the appendix.

Table 4—: Non-competitive Behavior Rates by Treatment

| | *Payoffs Within 20 Percent* | |
|---|---|---|
| | Mean | Median |
| Discrete | 0.1685<br>(0.0202) | 0.1379<br>(0.0178) |
| Continuous Slow | 0.2185<br>(0.0225) | 0.1894<br>(0.0192) |
| Continuous Instant | 0.2535<br>(0.0298) | 0.1980<br>(0.0092) |

*Notes:* Mean and median non-competitive behavior rates with bootstrapped standard errors. The percentage refers to the threshold defining when subjects are not exhibiting competitive behavior.

competitive behavior increases with fewer adjustment restrictions.

Note that we refrain from calling the behavior discussed above "collusion." Aside from the issues of using a somewhat loaded term, it is true that subjects in this game can be both non-competitive and earning trivial payoffs. However, a player would be better off undercutting and taking the entire market for *any* non-zero counterpart price, and our definition above encapsulates this wider notion of eased competition. Huck et al. (2003) define profitability with a maximin approach, and prove that collusion is profitable if and only if more than half of the players collude. They argue that with the difficulties of finding a reliable non-cooperative solution, players should be conservative and eschew competition only when they know it will be profitable. When applied to a two-player game with a price dimension added, the principle still seems to apply.

Even though subjects clearly displayed more anti-competitive behavior in continuous time, it is somewhat puzzling that non-competitive rates were relatively low. Figure IV.3 gives circumstantial evidence of how players were able to coordinate. It shows a subject pair in the middle of the session playing a *Continuous Instant* treatment. Shaded regions indicate non-competitive behavior between subjects. In the bottom panel on each figure, the thick lines are smoothed flow payoffs for each subject, while the actual flow payoffs are shown in the background. In the very beginning of the period, player 4 — the orange player — immediately adjusts her price to the maximum allowed (normalized to one) and her location to the middle. Notice that this reduced her payoff to lower than her counterpart's while she waited for her counterpart to fall in line with her strategy. The subject pair colluded for almost the entirety of the period, indicated by the blue bars in the payoff figure. The subject pair obtained much higher than average payoffs in this period as a result. Note that we are comfortable using the word "collude" here, as joint maximizing profits surely fits any definition of the term. On the other hand, Figure IV.4 shows a typical case of players following each other in the action space throughout the period. Player 4 is the same player that aggressively pushed for a collusive state in Figure IV.3, but is now matched with a more competitive player. Notice that she repeatedly attempts to drive the prices is higher, thus taking a momentary loss. But Player 4's counterpart immediately undercuts her, forcing her to be drawn into tight competition. At the end of the period, Player 4's payoffs are much lower than her counterpart's due to her attempts to ease competition. This kind of behavior was typical in the game, as "aggressive colluders" were only able to coax anti-competitive behavior out a relatively low number of counterparts.

We define an alternative state of non-competitive behavior that we call *Steady Positive Payoffs.* This concept abstracts away from a specific threshold, with a subject-pair in this state when both subjects have positive payoffs. The subject-pair's spell in Steady Positive Payoffs is then broken if one of the players undercuts her counterpart causing their profits to fall to zero. The rates that come from this definition are reported in Table 5. This shows that subjects were able to carve out some portion of the market well over 50 percent of the time. As expected, the

Table 5—: Steady Positive Payoffs Non-Competitive Rates by Treatment

| | Mean | Median |
|---|---|---|
| Continuous Instant | 0.6235 | 0.6162 |
| | (0.0161) | (0.0149) |
| Continuous Slow | 0.5402 | 0.5646 |
| | (0.019) | (0.0217) |
| Discrete | 0.5992 | 0.5914 |
| | (0.0255) | (0.0311) |

*Notes:* Mean and median non-competitive behavior rates with bootstrapped standard errors. Steady Positive Payoffs refers to spells in which both players in a subject pair have positive flow payoffs.

*Continuous Instant* treatment had the least intense competition. However, *Continuous Slow* treatments had lower non-competitive rates by this measure, and were lower than even the *Discrete* treatment. We speculate that this is a consequence of the location adjustment speed limit, which seemed to drive subjects to compete more aggressively on price alone and undercut more frequently.

Similarly, we examine the connection between a subject's tendency to undercut her counterpart, her counterpart's tendency to undercut, and the subject's payoff. This relationship is shown visually in Figure IV.5. The subject's tendency to undercut is shown on the x-axis, given as a count of the number of times a subject undercuts her counterpart — such that the counterpart's flow payoffs are reduced to zero by the move — in a specific period. This is plotted against the number of times that subject was undercut by her counterpart in the same period. As such, there is intentional "double counting" in the figure, with a subject being counted both as a subject and as another subject's counterpart. The colors represent the subject's payoff, with "hotter" colors indicating higher payoffs (note that the counterpart payoff is not shown in the figure). If multiple subject-pairs occupy the same cell, then the average payoff is taken.

We first note that abstaining from these aggressive undercuts are beneficial to the subject only if her counterpart exhibits similar restraint. This can be seen easily by the hot spot in the lower-right corner. It is clear that subjects that were more aggressive than their counterparts tended to have higher payoffs, as evidenced by the darker spots on the lower right section of the figure. Conversely, the subject's payoffs suffered if she met a counterpart that was more aggressive than her, as seen by the light areas in the top-left. We find this revealing of the incentives subjects faced in the game, as this shows that they consistently did better by being more competitive than their counterparts. However, it is also clear that successful collusion leads to higher payoffs, with high payoffs for the subject when both she and her counterpart did little to no undercutting. Finally, if both players were particularly aggressive and in relatively equal proportions, both subjects saw their payoffs suffer, as evidenced by the lightest region in the middle close to the 45 degree line.

Exit surveys from our experiments indicated that subjects did not initially attempt to come to tacit agreements with their counterparts, even among subjects with high non-competitive behavior rates. As such, we examine learning effects by treatment in Figure IV.6. It shows non-competitive behavior rates by period with the 20 percent threshold. Early in the sessions, rates were not statistically different between treatments. These differentiate relatively quickly, however, with continuous time treatments increasing and the discrete time treatment decreasing in non-competitive behavior. Our data from the *Continuous Slow* treatment are noisier, and hence is not as stable as the other two treatments and is not distinguishable from the *Continuous Instant* treatment.

## V. Discussion & Concluding Remarks

Our principal findings can be summarized briefly. First, subjects tended to locate close together in the middle of the action space, especially in continuous time treatments. In the *Continuous Instant* treatment with instantaneous price and location adjustments as well in the *Continuous Slow* treatment with delayed price adjustment, subjects were heavily congregated in the center, and were only 10 percent of the action space away from their counterpart on average. This lends strong support to Hotelling's principle of minimum differentiation.

Second, non-competitive behavior was higher in continuous time treatments. Our results are consistent with previous laboratory experiments that showed the ability to respond quickly can increase cooperation, though in this case it is not as nearly dramatic as in a simpler game such as a Prisoner's Dilemma. Our results show that the free and instantaneous adjustment gives the least intense competition, and we give circumstantial evidence of subjects aggressively pushing for a collusive states at the expensive of short-term payoffs.

However, this eased competition was far from ubiquitous, averaging about 25 percent of the time in settled behavior in the *Continuous Instant* treatment compared to roughly 17 percent in the *Discrete* treatment. Many subject-pairs failed to settle on a price equilibrium, even if one of the subjects in the pair was a willing collaborator. We take this as a reflection the difficulties in finding a theoretical equilibrium for the model. This, combined with our previous findings, can only lead us to conclude that Hotelling was largely correct in the principles and predictions of *Stability in Competition*, despite the fact that the model outlined in the seminal paper refused to yield an identifiable equilibrium. A passage from the original paper itself is particularly salient:

> *"For two independent merchants to come to an agreement of any sort is notoriously difficult, but when the agreement must be made all over again at frequent intervals, when each has an incentive for breaking*

> *it, and when it is frowned upon by public opinion and must be secret and perhaps illegal, then the pact is not likely to be very durable."*

With this in mind, we make a quiet appeal to economists, political scientists, and teachers of economic theory to use caution with their use of the "folk wisdom" version of the Hotelling model. Many applications of Hotelling's model — from voting theory to gas station placement — should be viewed with discretion in light of the instability shown in our experiment. It is clear that the introduction of vertical differentiation — as we followed Hotelling in doing so here — will obscure the clean result and require robust cooperation to achieve some degree of stability. That being said, our results give compelling evidence that the principle of minimum differentiation can be largely sustained even in the face of fierce competition on the vertical dimension, even if it is not with the same dependability that Hotelling originally predicted.

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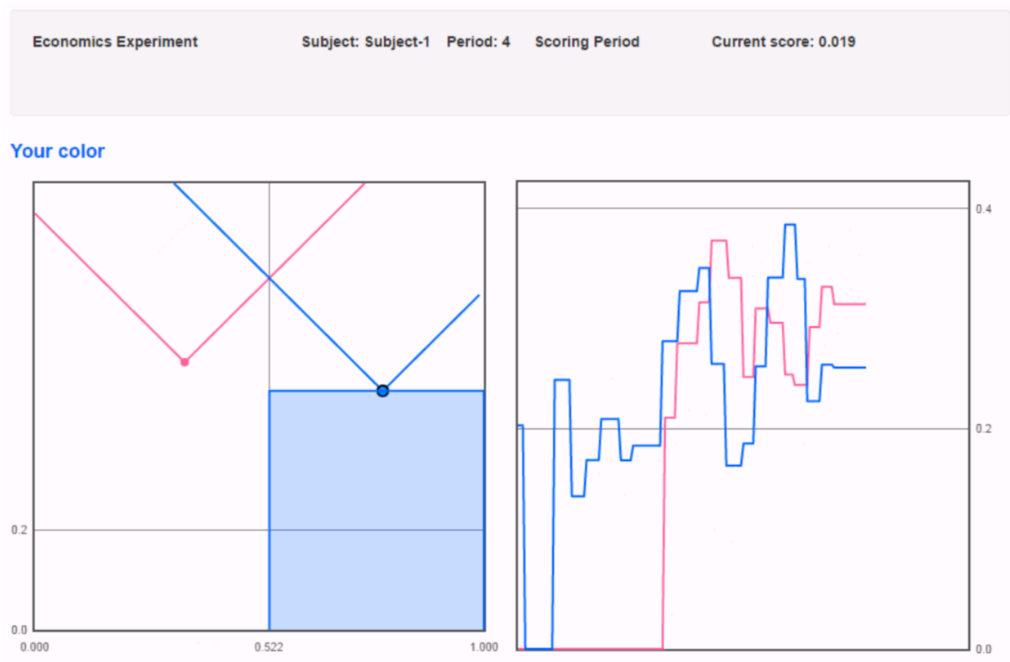
Figure III.1. : User Interfaces

(a) Continuous Time




(b) Discrete Time

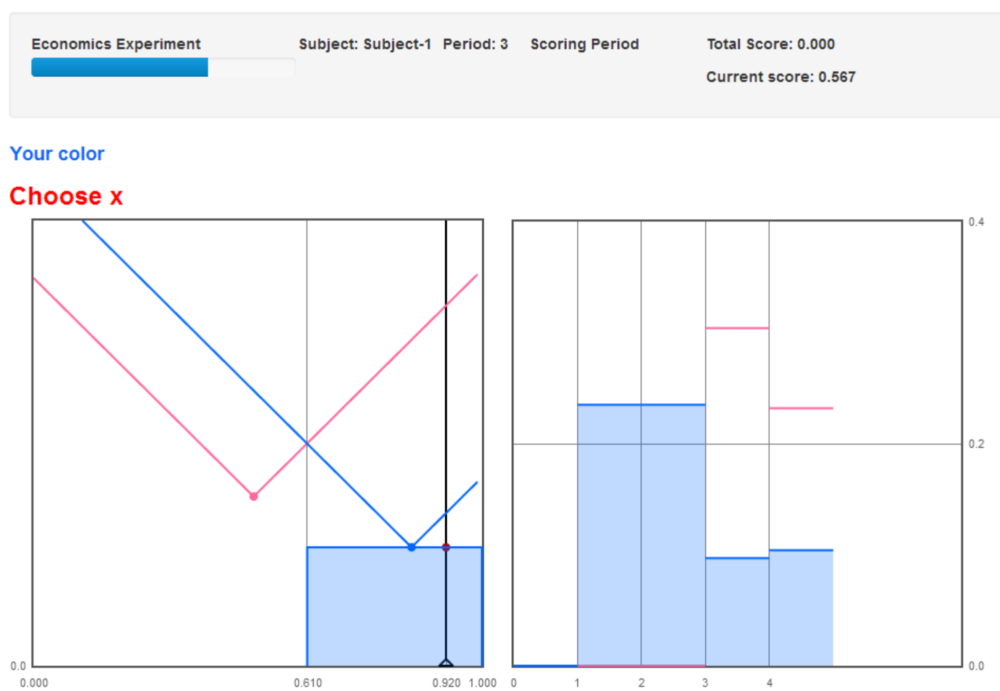
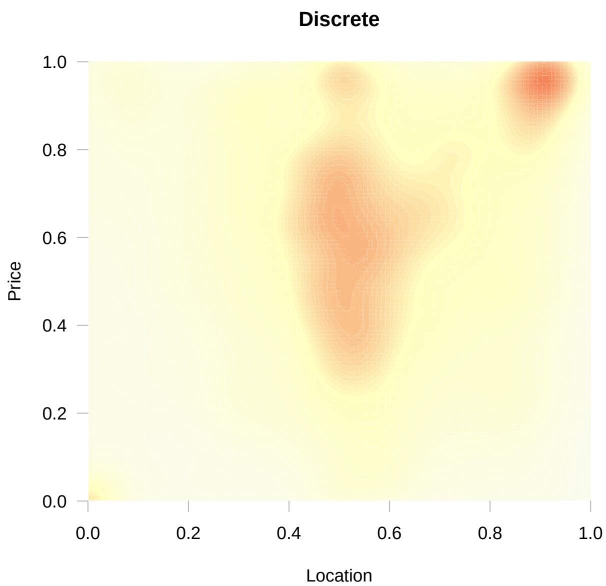
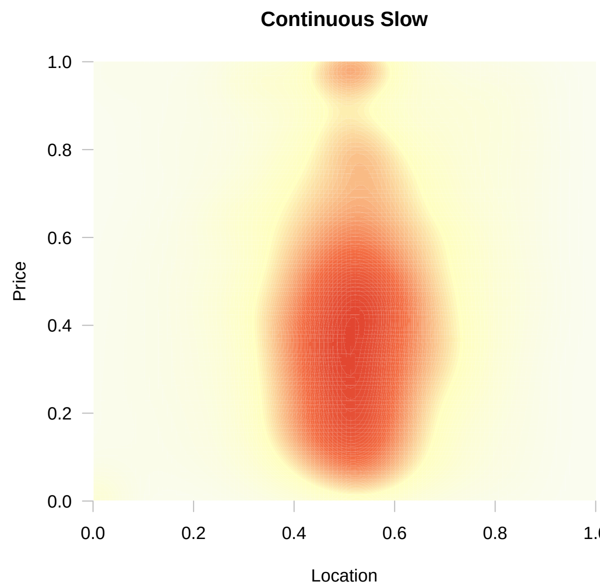


Figure IV.1. : Heat Maps of Subject Price and Location Decisions by Treatment

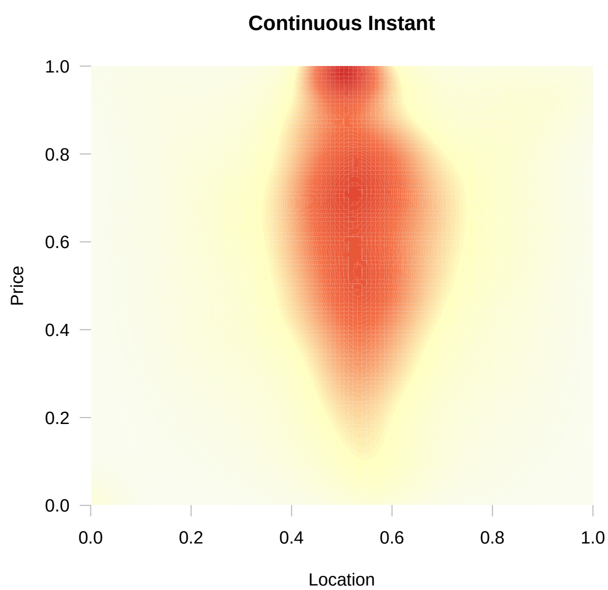
(a)




(b)



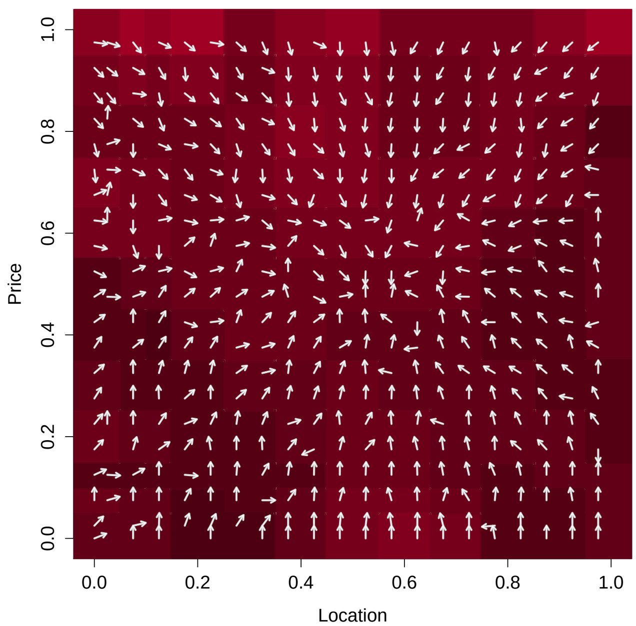

(c)



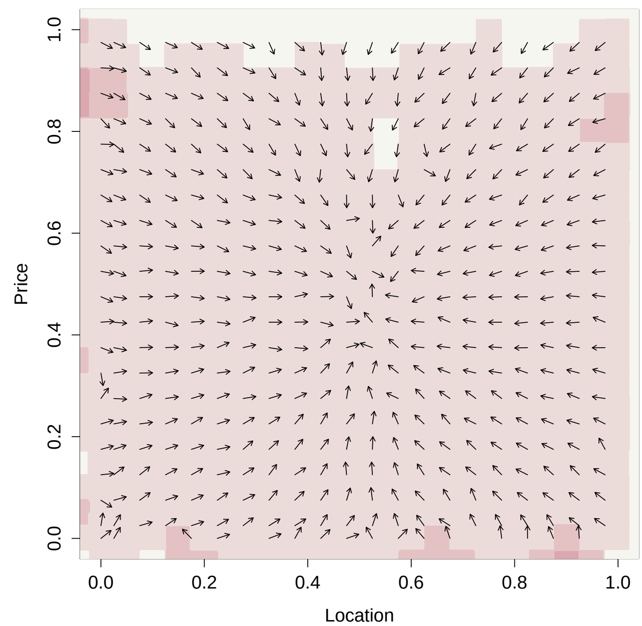

*Notes:* These figures show all players' price and location decisions by treatment. The heat maps run from cool to hot colors, with "hotter" colors indicating that players spent more time in those positions.

Figure IV.2. : Vector Fields of Subject Position Adjustments by Treatment

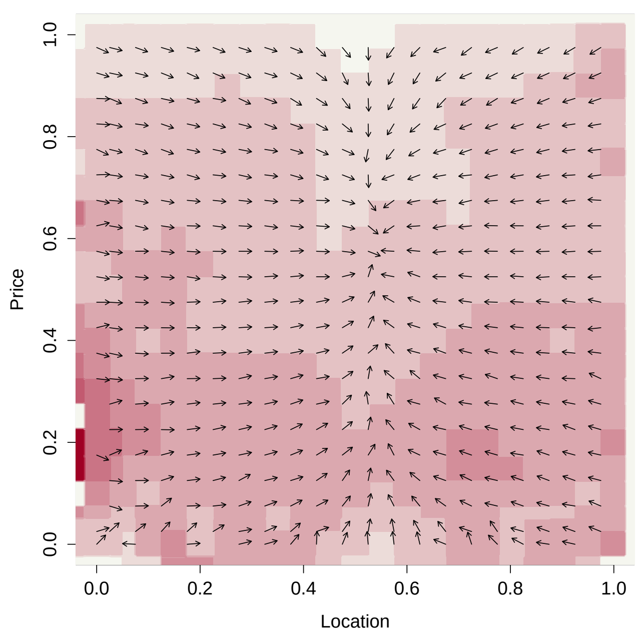
(a) Discrete




(b) Continuous Slow

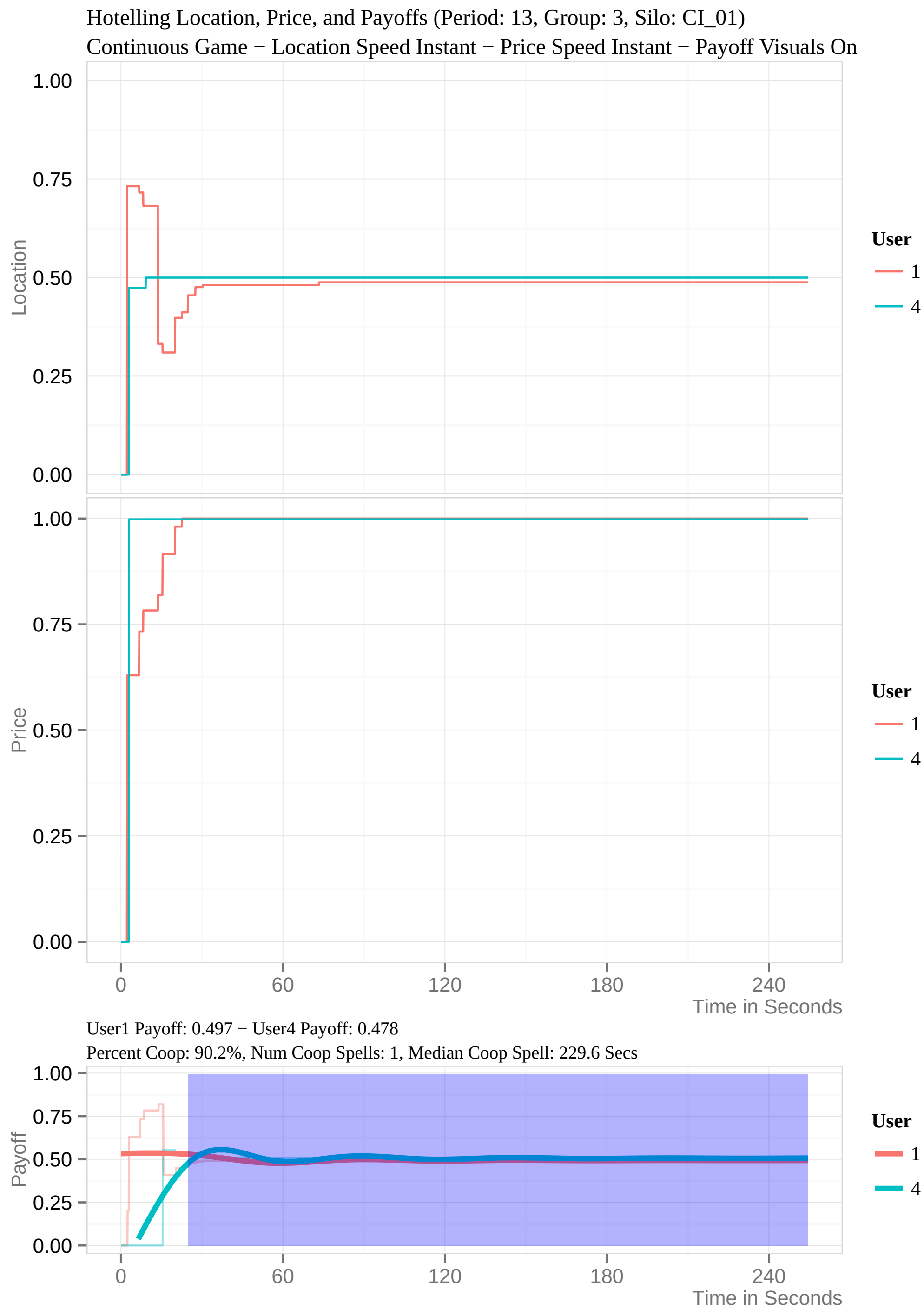



(c) Continuous Instant



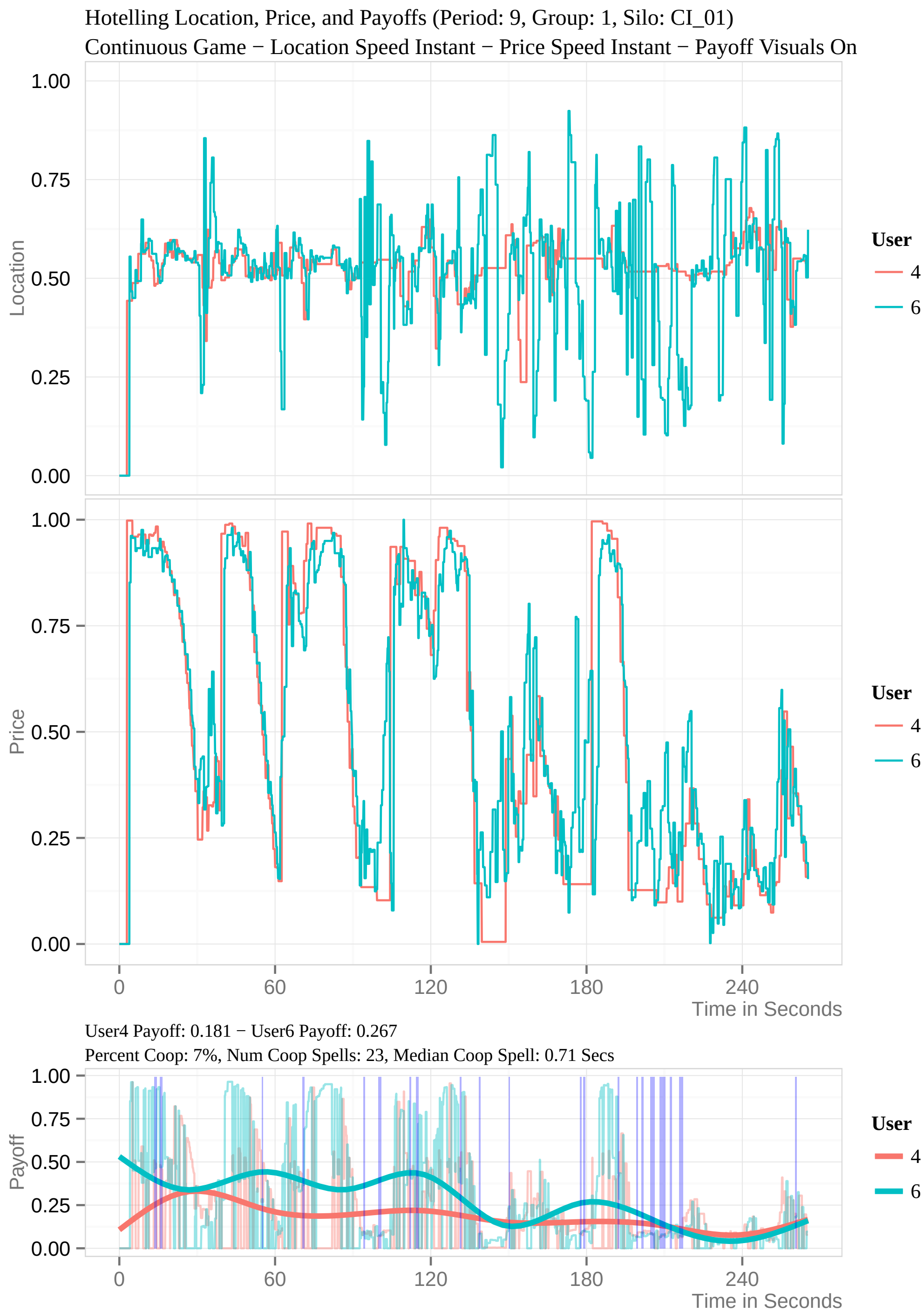

*Notes:* These figures show all players' price and location decisions by treatment. Arrows indicate average direction of action set changes starting from the arrow's neighborhood. The heat maps run from cool to hot colors, with "hotter" colors indicating that players were more likely to change their action set while in that neighborhood.

Figure IV.3. : Collusion Evidence, Successful Collusion



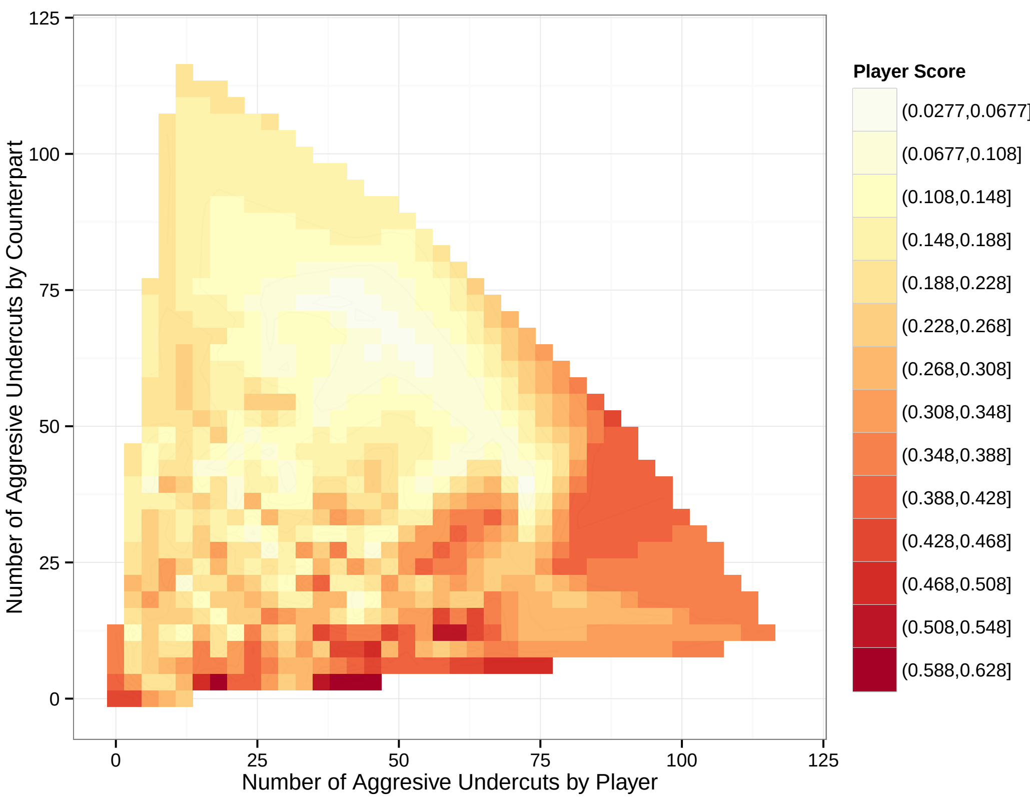

*Notes:* This figure shows two subjects that successfully colluded for the majority of a period in the *Continuous Instant* treatment. The first panel is the subject-pairs location decisions over time, the second panel is their price decisions over time, and the final panel is their flow payoff. Note that Player 4 was an "aggressive colluder," as she willingly took losses at the beginning of the period while waiting for her counterpart to conform.

Figure IV.4. : Collusion Evidence, Unable to Collude



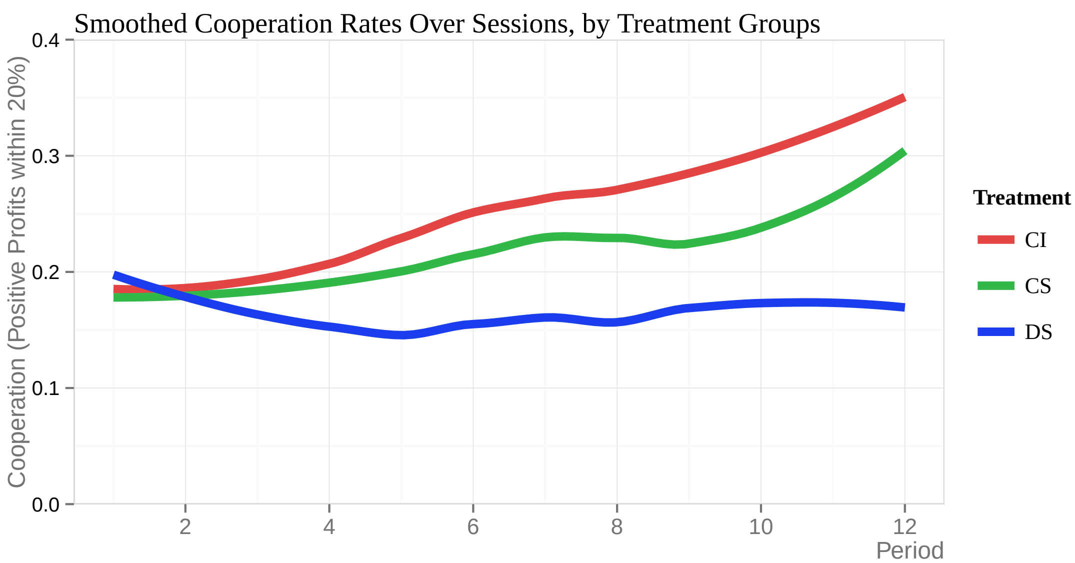

*Notes:* This figure shows two subjects that were unable to collude in a period in the *Continuous Instant* treatment. The first panel is the subject-pairs location decisions over time, the second panel is their price decisions over time, and the final panel is their flow payoff. Note that Player 4 is the same subject shown in Figure IV.3, but with a more aggressive counterpart.

Figure IV.5. : Subject-Pair Tendency to Undercut and Payoffs




*Notes:* An "aggressive undercut" is defined as a player movement that causes her counterpart's flow payoffs to be reduced to zero. The x-axis shows the number of instances in a period that the player completed this action, while the y-axis is the number of times her counterpart performed an aggressive undercut. The colors indicate the player's score at the end of the period, with darker colors indicating a higher score.

Figure IV.6. : Learning Effects




*Notes:* This shows smoothed non-competitive behavior rates by period, separated by treatment. Rates are measured by the 20 percent threshold, with 90 percent confidence intervals shown in the background.

## Additional Tables and Figures

Table A1—: Non-competitive Rates by Treatment, All Periods

| | *10%* | | *20%* | |
|---|---|---|---|---|
| | Mean | Median | Mean | Median |
| Continuous Instant | 0.1605 | 0.1072 | 0.2669 | 0.2053 |
| | (0.0313) | (0.0076) | (0.0334) | (0.0143) |
| Continuous Slow | 0.1413 | 0.1006 | 0.2623 | 0.2311 |
| | (0.0191) | (0.0126) | (0.0201) | (0.0184) |
| Discrete | 0.097 | 0.0712 | 0.1734 | 0.1489 |
| | (0.0137) | (0.0088) | (0.02) | (0.0169) |

*Notes:* Mean and median non-competitive rates with bootstrapped standard errors. The percentage refers to the threshold defining when subjects are not competing.

## Instructions to Participants

### *B1. Continuous and Continuous Slow Instructions*

Welcome! You are about to participate in an experiment in the economics of decision making. If you listen carefully and make good decisions, you could earn a considerable amount of money that will be paid to you in cash at the end of the experiment.

Please remain silent and do not look at other participants' screens. If you have any questions, or need assistance of any kind, please raise your hand and we will come to you. Do not attempt to use the computer for any other purpose than what is explicitly required by the experiment. This means you are not allowed to browse the internet, check emails, etc. If you disrupt the experiment by using your smart phone, talking, laughing, etc., you may be asked to leave and may not be paid. We expect and appreciate your cooperation today.

**The Basic Idea**

The experiment will be divided into a number of periods, and each period you will be matched anonymously with a counterpart, who is another participant in today's experiment.

Throughout each period you will choose a position within a range of possible positions. The number of points you earn each period will depend on your choice and the choice(s) of your counterpart.

At the end of the session, two periods will be randomly chosen to be the paid periods. The number of points you earned in those periods will be converted to US dollars at a rate shown on the whiteboard, and paid to you in cash.

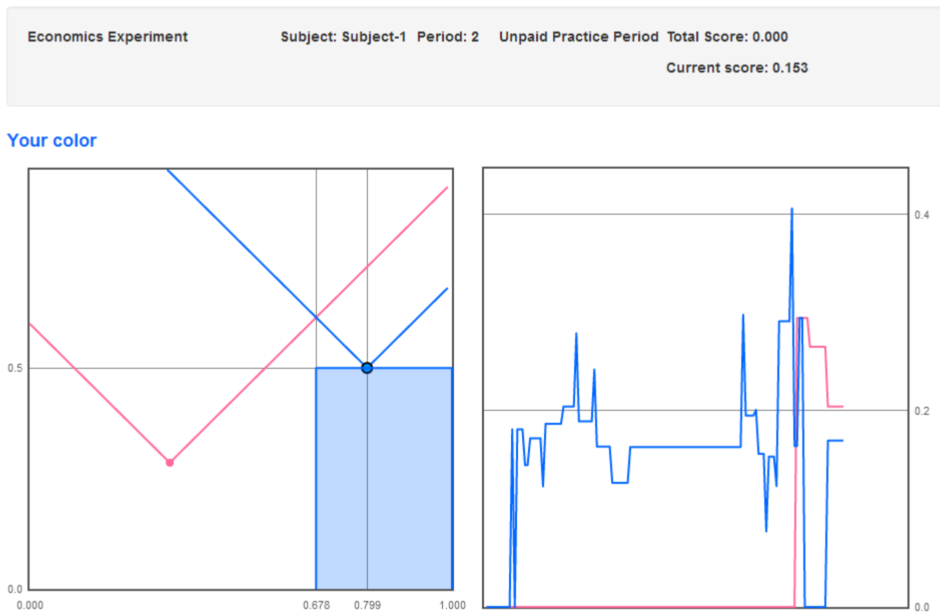
**Choosing Your Position**

Figure B1 shows the user interface. Crosshairs will follow your mouse as it moves over the screen, but your location will not be adjusted until you click the mouse. You will be able to select your position by clicking on your desired position with your mouse on the screen. However, in some periods your position will *not* adjust instantly. Instead, your position will slowly adjust to the location you selected, which will be indicated by a grey dot on your screen. Note that your position may be able adjust horizontally and vertically equally quickly, or your position may be able to adjust more quickly along one dimension. Also note that your counterpart will always have the same ability to adjust her position as you.

**How You Earn Points**

You earn points at a rate proportional to the size of the action area you control. At every moment during the experiment you will see your position and earnings, and the position and earnings of your counterpart. In Figure B1, your position is indicated by the blue dot in the box on the left side. Note that your color will always be indicated by the color of the words "Your color" above the box on the left. Your flow of earnings is shown in the box on the right by a blue line. Similarly, the position of your counterpart is indicated by the pink dot on the left, and the current earnings of your counterpart is shown by the pink line on the right. Note that your flow of earnings is also shown as a number in the box at the top of the screen under "Current score."

Figure B1. : User Interface




Note that the figure also includes lines running away from your position and from your counterpart's position, as well as a shaded area indicating the action area you control. The intersection of your line with your counterpart's line determines the size of the action area you control.

**Periods**

Periods will last several minutes. After a brief intermission, a new period will begin with new counterparts who may be different participants than in the previous period.

**Frequently asked questions**

1) Is this some kind of psychological experiment with an agenda you haven't told us?

a) Answer: No. It is an economics experiment. If we do anything deceptive or don't pay you cash as described then you can complain to the campus Human Subjects Committee and we will be in serious trouble. These instructions are meant to clarify the game and show you how you earn money; our interest is simply in seeing how people make decisions.

2) Will there be practice periods?

a) Answer: Yes. You will have three unpaid 30-second practice periods. Use this time to familiarize yourself the controls of the software, and how your choice and the choices of your counterparts affect your flow payoffs.

### *B2. Discrete Instructions*

Welcome! You are about to participate in an experiment in the economics of decision making. If you listen carefully and make good decisions, you could earn a considerable amount of money that will be paid to you in cash at the end of the experiment.

Please remain silent and do not look at other participants' screens. If you have any questions, or need assistance of any kind, please raise your hand and we will come to you. Do not attempt to use the computer for any other purpose than what is explicitly required by the experiment. This means you are not allowed to browse the internet, check emails, etc. If you disrupt the experiment by using your smart phone, talking, laughing, etc., you may be asked to leave and may not be paid. We expect and appreciate your cooperation today.

**The Basic Idea**

The experiment will be divided into a number of periods, and each period will be broken up into subperiods. For each period, you will be matched anonymously with a counterpart, who is another participant in today's experiment.

Throughout each period you will choose a position within a range of possible positions. The number of points you earn each period will depend on your choice and the choice(s) of your counterpart.

At the end of the session, two periods will be randomly chosen to be the paid periods. The number of points you earned in those periods will be converted to US dollars at a rate shown on the whiteboard, and paid to you in cash.

**Choosing Your Position**

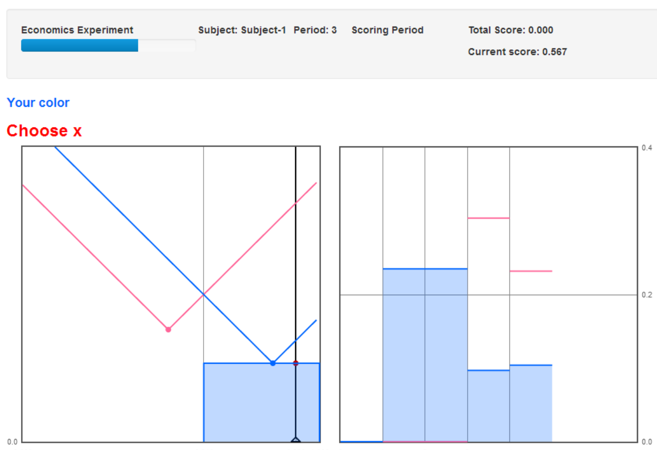
Figures 1 and 2 show the user interface. A gray line will follow your mouse as it moves over the screen, but your location will not adjust until you click the mouse. You will be able to select your position by clicking on your desired position with your mouse on the screen. This will proceed in stages. At the beginning of the period, you are in the first subperiod. In this subperiod, you will only be able to adjust your position along the x-axis (horizontally). In the next subperiod, you will be able to adjust your position only along the y-axis (vertically). There will be between one and four subperiods in which you can only adjust your position vertically. You will be able to adjust your position within a subperiod, but your final position is the position you have selected when the subperiod ends.

**How You Earn Points**

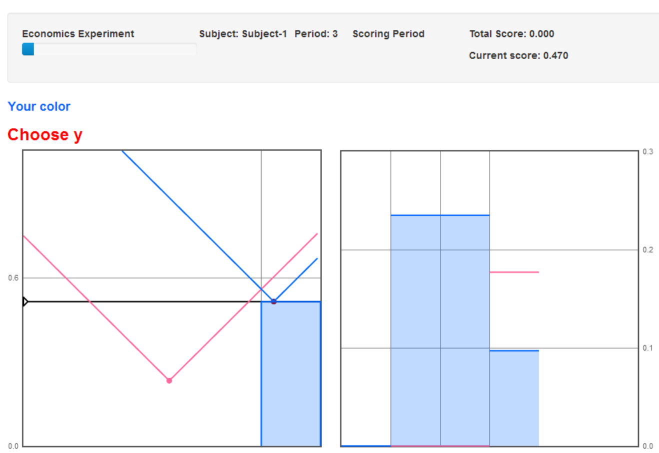
You earn points at a rate proportional to the size of the action area you control. At every subperiod during the experiment you will see your position and earnings from the pervious subperiod, and the position and earnings of your counterpart from the previous subperiod. In Figure B2a, your position from the previous subperiod is indicated by the blue dot in the box on the left side. Note that your color will always be indicated by the color of the words "Your color" above the box on the left. Your flow of earnings is shown in the box on the right by a blue area. Similarly, the position of your counterpart is indicated by the pink dot on the left, and the current earnings of your counterpart is shown by the pink line on the right. Note that your flow of earnings is also shown as a number in the box at the top of the screen under "Current score." Also note that you do not receive earnings after making only a horizontal adjustment of your position, as your earnings depend on both your horizontal *and* vertical positions. The black line and red dot indicate the position you currently have selected for your horizontal position, which you are free to adjust until the end of the subperiod. Figure B2b is identical to Figure B2a, except that the black line and red dot indicate the position you currently have selected for your vertical position.

Figure B2. : User Interfaces During Practice Periods

(a) Adjusting Position Horizontally




(b) Adjusting Position Vertically



Note that the figure also includes lines running away from your position and from your counterpart's position, as well as a shaded area indicating the action area you control. The intersection of your line with your counterpart's line determines the size of the action area you control.

**Periods**

The time remaining in the subperiod is shown by the progress bar at the top of the screen. After a brief intermission, a new subperiod will begin. At the end of each *period*, you will be matched with new counterparts who may be different participants than in the previous period.

**Frequently asked questions**

1) Is this some kind of psychological experiment with an agenda you haven't told us?

    a) Answer: No. It is an economics experiment. If we do anything deceptive or don't pay you cash as described then you can complain to the campus Human Subjects Committee and we will be in serious trouble. These instructions are meant to clarify the game and show you how you earn money; our interest is simply in seeing how people make decisions.

2) Will there be practice periods?

    a) Answer: Yes. You will have two unpaid 100-second practice periods. Use this time to familiarize yourself the controls of the software, and how your choice and the choices of your counterparts affect your flow payoffs.