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**LOOK-UPS AS THE WINDOWS OF THE STRATEGIC SOUL: STUDYING  
COGNITION VIA INFORMATION SEARCH IN GAME EXPERIMENTS**

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Based on joint work with Miguel Costa-Gomes, University of York, and  
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(particularly on Costa-Gomes and Crawford, "Studying Cognition via Information  
Search in Two-Person Guessing Game Experiments," in preparation 2006)

**Introduction**

Neuroeconomics rests on the premise that because human decisions are the result of cognitive processes, evidence about neural correlates of those processes will be helpful in formulating and testing theories of decisions.

Some scholars (e.g. Faruk Gul and Wolfgang Pesendorfer, "The Case for Mindless Economics," 2005) have argued that neuroeconomics is beyond the pale (my phrase, not theirs) because mainstream economic theory was meant to explain only decisions, and so should only be tested by observing decisions.

They view neuroeconomics as a radical departure in part because neural data concern involuntary, unconscious processes. Because those processes are not decisions, "our" theories cannot be about them.

This talk will explore some middle ground, discussing game experiments in which some payoff-relevant information is hidden but freely accessible to subjects; and focusing on issues that arise in using subjects' information searches, along with their decisions, to identify the decision rules that determine their behavior.

Because these analyses of search use an explicit model of subjects' cognition to analyze the data, they raise some of the same issues neuroeconomics raises,

But unlike neural correlates of cognition, search is a voluntary, conscious process. Thus with some adjustments, "our" theories can be made to be about it.

Although incorporating neural data into analyses of games and decisions is harder than incorporating search data, I hope that this exploration will bring us a step closer to agreement on how (or whether) to do neuroeconomics.

## Outline

The talk begins by reviewing the key features of the methods and analyses in some recent papers that use search to study cognition and behavior in games.

It then illustrates how combining search with a rudimentary analysis of cognitive processes can better identify subjects' decision rules, sometimes even directly revealing the algorithms subjects use to choose their decisions.

It further illustrates the possibilities for such analyses by raising questions they can answer but which are likely to continue to resist analysis via decisions alone.

The proposed analysis of cognitive processes rests on assumptions that stylize regularities in how experimental subjects' cognition determines search.

I close by outlining a slightly deeper explanation of those assumptions, which views search strategies as rational decisions under plausible assumptions about the benefits and costs of search and constraints on working memory.

(The proposed explanation differs from classical search theory more in purpose than in methods. So if this stuff isn't economics, then neither is search theory....)

# **Game Experiments that Study Cognition by Monitoring Information Search**

## **a. Overall structures**

The experiments I discuss randomly and anonymously paired subjects to play series of different but related 2-person games, with no feedback between games.

The designs suppress learning from experience and repeated-game effects in order to elicit subjects' initial responses, game by game.

The goal is to focus on the question of how players model others' decisions by studying strategic thinking "uncontaminated" by learning from experience (which in stationary environments can make even amoebas converge to equilibrium).

("Eureka!" learning remains possible, but it can be tested for and seems rare.)

(The results yield insights into cognition that also help us think about how to model learning from experience, but that's another story.)

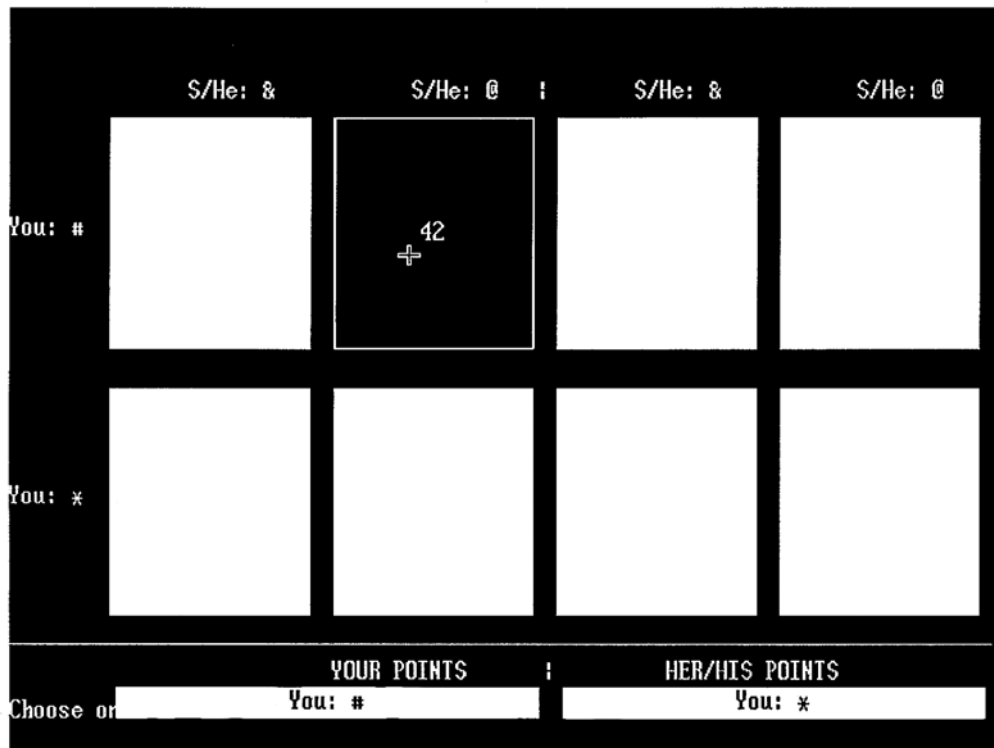
For simplicity, I assume risk-neutrality throughout the discussion; but I sometimes allow nonpecuniary, "social" preferences as indicated below.

## b. Monitoring search for hidden but freely accessible payoff information

The methods for monitoring search originated in MouseLab studies of decisions. (MouseLab is an automated way to track search as in eye-movement studies; see John Payne, James Bettman, and Eric Johnson, *The Adaptive Decision Maker*, 1993. A modern analog, with many more capabilities, is used in Joseph Wang, Michael Spezio, and Camerer, "Pinocchio's Pupil: Using Eyetracking and Pupil Dilation To Understand Truth-telling and Deception in Games," 2006.)

In the MouseLab game designs discussed here, the structures are publicly announced except for hidden, varying payoff parameters, to which subjects are given free access, game by game, before making their decisions.

Access is via an interface like this (for a 2x2 matrix game in CGCB, *EMT* 2001):



With search costs as low as subjects' search patterns make them seem, free access makes the entire structure effectively public knowledge, so results can be used to test theories of behavior in complete-information versions of the games.

(Except that nonpecuniary, "social" components of subjects' preferences, like risk aversion, are privately known; but this makes little difference for my purposes.)

These designs also maintain tight control over subjects' motives for search by making information from previous plays irrelevant to current payoffs.

### c. Extensive-form designs

CJ1. Colin Camerer, Eric Johnson, Talia Rymon, and Sankar Sen, "Cognition and Framing in Sequential Bargaining for Gains and Losses," in Kenneth Binmore, Alan Kirman, and Piero Tani (editors), *Frontiers of Game Theory*, 1993

CJ2. Johnson, Camerer, Sen, and Rymon, "Detecting Failures of Backward Induction: Monitoring Information Search in Sequential Bargaining," *Journal of Economic Theory* 2002 ("CJ2")

(The 9-year difference between the dates of publication of CJ1 (in a conference volume that, fortunately for me, just came in the mail one day) and CJ2 (in *JET*) is a rough measure of our profession's receptiveness to genuinely new ideas.)

In CJ1 and CJ2, subjects played series of two-person, three-round alternating-offers bargaining games in which the "pie" varies across rounds to simulate discounting at a common rate, with different partners and pies each round.

Within a publicly announced structure, each game was presented to subjects as a series of pies, with the pies normally concealed but subjects allowed to look them up as often as desired, one at a time.

(Subjects were not allowed to write down the pies, and the frequencies with which they looked them up made clear that they did not memorize them.)

At roughly the same time, CJ did a MouseLab study of forward induction in simple extensive-form games, reported much later in:

CJ3. Camerer and Johnson, "Thinking about Attention in Games: Backward and Forward Induction," in Isabel Brocas and Juan Carrillo (editors), *The Psychology of Economic Decisions, Volume Two: Reasons and Choices*, Oxford, 2004

#### **d. Normal-form designs**

CGCB. Miguel Costa-Gomes, Vincent Crawford, and Bruno Broseta, "Cognition and Behavior in Normal-Form Games: An Experimental Study," *Econometrica* 2001

(The word "behavior" in the title is meant to include search as well as decisions.)

CGCB adapted CJ's methods to study cognition via search for hidden payoffs in matrix games, eliciting initial responses to 18 games with various kinds of iterated dominance or with unique pure-strategy equilibria without dominance. These games explore different aspects of strategic thinking than CJ's.

Within a publicly announced structure, each game was presented via MouseLab, which normally concealed payoffs but allowed subjects to look up their own and their partner's payoffs for each decision combination. Players' payoffs were spatially separated to ease cognition and make search more informative.

(Subjects were not allowed to write, and did not memorize the payoffs.)

CGC. Costa-Gomes and Crawford, "Cognition and Behavior in Two-Person Guessing Games: An Experimental Study," *American Economic Review*, in press 2006 (posted with supporting materials at <http://dss.ucsd.edu/~vcrawfor/#Guess>)

CGC studied cognition via decisions and search for hidden payoff parameters, eliciting initial responses to 16 dominance-solvable two-person guessing games. These games explore different aspects of strategic thinking than CGCB's or CJ's.

Within a publicly announced structure, each game was presented via MouseLab, which normally concealed the parameters but allowed subjects to look them up.

(Subjects were not allowed to write, and did not memorize the parameters.)

## Design Desiderata for Studying Cognition via Search

In studying cognition via search, three design features are particularly desirable:

(i) Allowing subjects to search for a small number of hidden payoff parameters within a simple, publicly announced structure; this allows subjects to focus on the task of predicting others' responses without getting lost in details of the structure.

(ii) Independently separating the implications of leading decision rules for search and decisions; this makes it possible to study the relationship between them, which multiplies the power of the design to identify subjects' rules.

(iii) Allowing search patterns to vary in a high-dimensional space; this makes search more informative and allows greater separation of rules via search.

CJ1's and CJ2's extensive-form designs (and to a lesser extent, CJ3's) do well on (i), pretty well on (ii), but poorly on (iii) (with search roughly one-dimensional).

CGCB's normal-form matrix-game design does well on (ii), pretty well on (iii) (with search roughly three-dimensional: up-down in own payoffs, left-right in other's payoffs, transitions from own to other's payoffs), but poorly on (i) (search is for 8-16 payoffs in games with no common structure beyond being matrix games).

CGC's two-person guessing game design does well on (i), (ii), and (iii).

Its simple parametric structure also makes leading rules' search implications (almost) independent of the game.

(The lack of structure in CGCB's design makes rules' search implications vary from game to game in ways so complex you need a "codebook" to identify them.)

I will now use CGC's analysis to illustrate how combining search with a rudimentary analysis of cognitive processes can better identify subjects' decision rules; and then how analyzing search can answer other interesting questions about cognition and behavior in games.

(The slides in the Appendix discuss CJ's and CGCB's analyses in more detail.)

## Costa-Gomes and Crawford's Two-Person Guessing Game Experiments

In CGC's guessing games, each player has his own lower and upper limit, both strictly positive; but players are not required to guess between their limits.

Guesses outside the limits are automatically adjusted up to the lower or down to the upper limit as necessary (a trick to enhance separation of rules via search).

Each player also has his own target, and his payoff increases with the closeness of his adjusted guess to his target times the other's adjusted guess.

The targets and limits vary independently across players and 16 games, with the targets either both less than one, both greater than one, or mixed.

(In the previous guessing experiments of Rosemarie Nagel (1995 *AER*) and Ho, Camerer, and Keith Weigelt (1998 *AER*; "HCW"), targets and limits were always the same for both players, and varied either only across treatments or not at all.)

The 16 games subjects played are finitely dominance-solvable in 3-52 rounds, with essentially (because the only thing about a guess that matters is its adjusted guess) unique equilibria determined by the targets and limits in a simple way.

E.g. in game  $\gamma 4\delta 3$ , player  $i$ 's limits and target are [300, 500] and 1.5 and player  $j$ 's are [300, 900] and 1.3. The product of targets  $1.5 \times 1.3 > 1$ , which implies that players' equilibrium adjusted guesses are determined (at least indirectly) by their upper limits. Player  $i$ 's equilibrium adjusted guess equals his upper limit of 500, but player  $j$ 's equilibrium adjusted guess is below his upper limit at 650.

The way in which equilibrium is determined here, by players' upper limits when the product of their targets is greater than 1, or by players' lower limits when the product of their targets is less than 1, is general in CGC's guessing games.

CGC's design exploits the discontinuity of the equilibrium correspondence when the product is 1 by including some games that differ mainly in whether the product is slightly greater, or slightly less, than 1:

Equilibrium responds very strongly to such differences, but empirically plausible non-equilibrium decision rules are largely unmoved by them.

The way in which equilibrium is jointly determined by both players' parameters also helps to separate the search implications of equilibrium and other rules.

## Leading Strategic Decision Rules or *Types*

CGC's analysis of decisions, like Stahl and Wilson's (1995 *GEB*) and CGCB's, uses a structural non-equilibrium model of initial responses in which each subject's decisions are determined by one of several decision rules or *types*.

(Types play a central role in CGC's and CGCB's model of cognition, search, and decisions, which takes a procedural view of decision-making, in which a subject's type determines his search and his type and search determine his decision.)

I focus on CGC's normal-form types, assuming risk-neutrality with no social preferences. (The Appendix discusses CJ2's extensive-form analogs of some of these types.) CGC's types include:

*L1*, which best responds to a uniform random *L0* "anchoring type"

(*L0* usually has 0 estimated frequency or is confounded with the error structure.)

*L2* (*L3*), which best responds to *L1* (*L2*)

(*Lk* for  $k > 0$  is rational, but deviates from equilibrium because it uses a simplified model of others' decisions. It is  $k$ -level rationalizable and so coincides with equilibrium in games that are  $k$ -dominance solvable. With plausible population type frequencies, this yields an inverse relationship between strategic complexity and equilibrium compliance as is often observed, e.g. CGCB, Table II.)

(Previous analyses have considered alternative definitions of *L2*, etc.: Stahl and Wilson's *L2* best responds to a noisy *L1*; and Camerer, Teck-Hua Ho, and Juin-Kuan Chong's ("A Cognitive Hierarchy Model of Games," 2004 *QJE*) *L2* best responds to an estimated mixture of *L1* and *L0*. CGC discuss the evidence.)

*Equilibrium*, which makes its equilibrium decision

*D1* (*D2*), which does one round (two rounds) of deletion of dominated decisions and then best responds to a uniform prior over the other's remaining decisions

(By a quirk of our notation, *L2* is *D1*'s cousin, and *L3* is *D2*'s. It is those pairs whose guesses are perfectly confounded in Nagel's games; and in two-person games, *Lk* guesses are  $k$ -rationalizable, just as *Dk-1*'s are.)

*Sophisticated*, which best responds to the probabilities of other's decisions, as estimated from subjects' observed frequencies

## CGC's Results for Decisions

The large strategy spaces and independent variation of targets and limits in CGC's design enhance separation of types' implications for decisions, to the point where many subjects' types can be precisely identified from guesses alone.

Of 88 subjects, 43 made guesses that complied *exactly* (within 0.5) with one type's guesses in 7-16 of the games (20 *L1*, 12 *L2*, 3 *L3*, and 8 *Equilibrium*).

CGC's Figure 2 on the next slide shows the "fingerprints" of the 12 subjects whose apparent types were *L2*. Of their 192 (= 12×16) guesses, 138 (72%) were exact. With games in Figure 2's unrandomized order, exact *L2* guesses must track the pattern: 105, 175, 175, 300, 500, 650, 900, 900, 250, 225, 546, 455, 420, 525, 315, 315, which is even more complex in randomized order.

Given how strongly CGC's design separates types' guesses (CGC, Figure 5), and that guesses could take 200-800 different rounded values in their games, these subjects' compliance is far higher than could occur by chance.

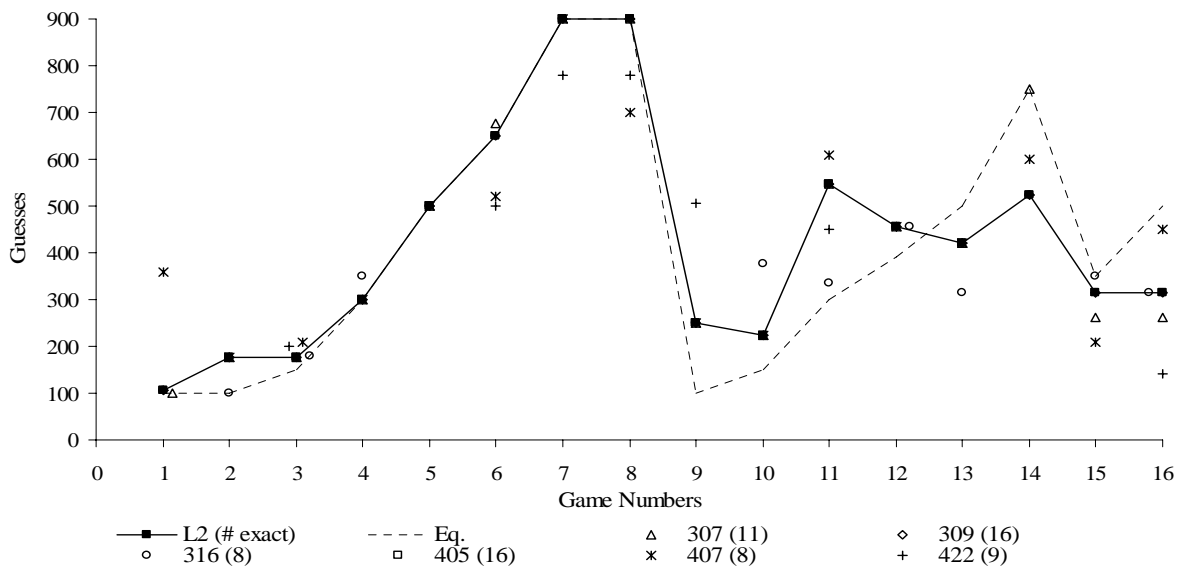
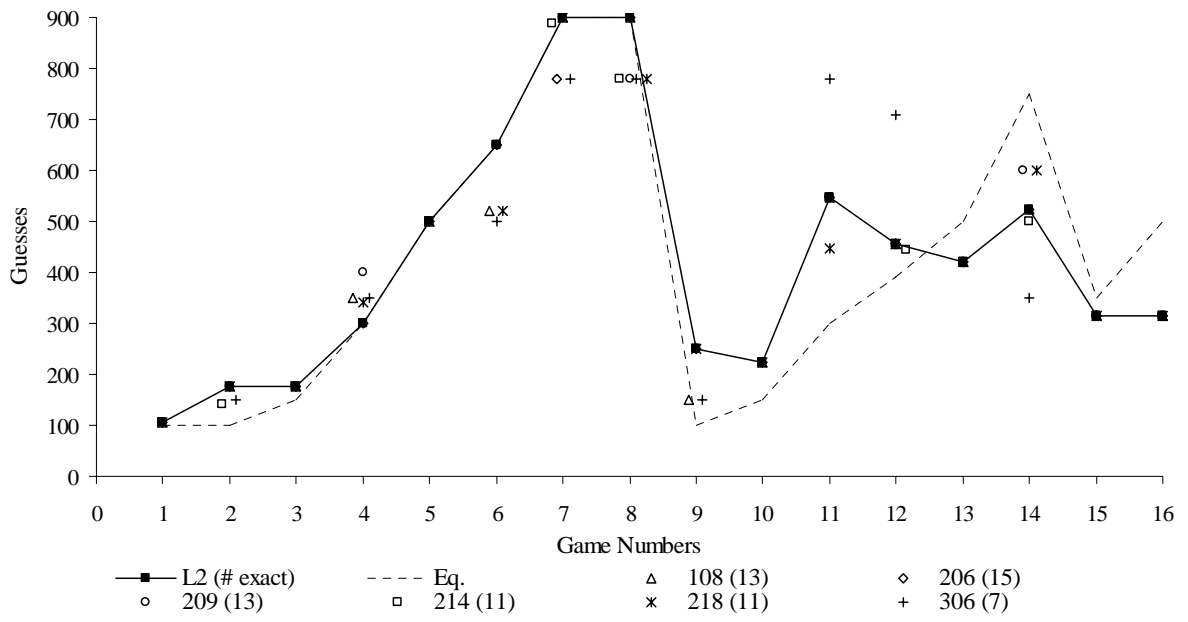
Further, because the types specify precise, well-separated guess sequences in a very large space of possibilities, their high exact compliance rules out (intuitively or econometrically) alternative interpretations of their behavior.

In particular, because the types build in risk-neutral, self-interested rationality and perfect models of the game, the deviations from equilibrium of the 35 subjects whose apparent types are *L1*, *L2*, or *L3* can be attributed to non-equilibrium beliefs rather than irrationality, risk aversion, altruism, spite, or confusion.

(By contrast, in Stahl and Wilson's or CGCB's matrix-game designs, even a perfect fit does not distinguish a subject's best-fitting type from nearby omitted types; and in Nagel's and HCW's guessing-game designs, with large strategy spaces but with each subject playing only one game, the ambiguity is worse.)

CGC's other 45 subjects' types are less apparent from their guesses; but *L1*, *L2*, *L3*, and *Equilibrium* are still the only ones that show up in econometric estimates.

Unlike the often-suggested interpretation of Nagel's and HCW's results—that subjects are explicitly performing finitely iterated dominance—CGC's clear separation of *L<sub>k</sub>* from *D<sub>k-1</sub>* allows us to show that *D<sub>k</sub>* types don't exist in any significant numbers, at least in this setting. *Sophisticated*, which in this design is clearly separated from *Equilibrium*, also doesn't exist in significant numbers.



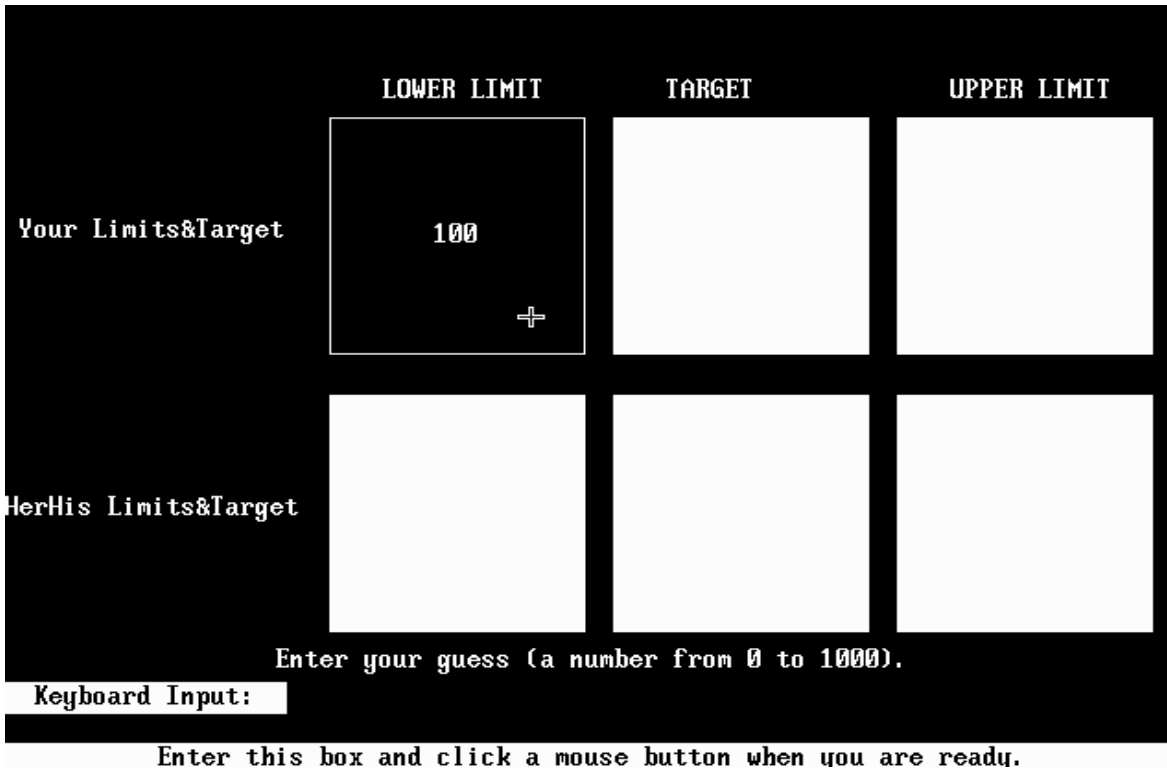
**Figure 2. "Fingerprints" of 12 Apparent L2 Subjects**

(Only deviations from L2's guesses are shown. 138 (72%) of these subjects' 192 guesses were exact L2 guesses.)

## Monitoring Search via MouseLab in Two-Person Guessing Games

CGC's games also create new possibilities for studying cognition via search.

Within a publicly announced structure, each game was presented via MouseLab, which normally concealed the targets and limits but allowed subjects to look them up as often as desired, one at a time (click option, versus CJ's rollover option).



CGC's Figure 6. Screen Shot of the MouseLab Display

## **Where is the Information in Subjects' Searches?**

Studying cognition via search requires a model of how cognition shows up in subjects' look-up sequences. Different papers take different positions on this:

CJ gave roughly equal weight to look-up durations and to the numbers of look-ups of each pie ("acquisitions") and the transitions between pies.

Ariel Rubinstein, "Instinctive and Cognitive Reasoning: A Study of Response Times," 2005, which considers some matrix games, considered only durations.

CJ's and Rubinstein's analyses were also conducted at a very high level of aggregation, both across subjects and over time.

Xavier Gabaix, David Laibson, Guillermo Moloche, and Stephen Weinberg, "Costly Information Acquisition: Experimental Analysis of a Boundedly Rational Model," *American Economic Review*, in press 2006, focused on numbers of look-ups (as opposed to durations) and considered some aspects of their order too.

Gabaix et al. also conducted their analysis mostly at a high level of aggregation.

## **Studying Cognition via Numbers and Order of Subjects' Look-ups**

CGCB and CGC took a different position:

They argued that cognition is sufficiently heterogeneous and search sufficiently noisy that they are best studied at the individual level.

They also assumed that which look-ups subjects make, in which order, reveals at least as much information about cognition as durations or transition frequencies.

This should not be surprising, because simple theories of cognition more readily suggest roles for which look-ups subjects make, in which orders, than durations.

(No claim that durations are irrelevant was intended, just that they don't deserve the priority they have been given. CGCB (Table IV) do present some results on durations, under the heading of "gaze times.")

## **Types as Models of Cognition, Search, and Decisions**

CGC's and CGCB's models of cognition, search, and decisions (which differ slightly) are based on a procedural view of decision-making, in which a subject's type determines his search, and his type and search then determine his decision.

This view is the key to linking cognition, search, and decisions in the analysis.

(Because a type's search implications depend not only on what decisions it specifies, but why, something like a types-based model seems necessary here.)

Each type is naturally associated with algorithms that process payoff information into decisions.

The analysis uses those algorithms as models of cognition, deriving a type's search implications under simple assumptions about how it determines search.

Without further assumptions, nothing precludes a subject's scanning and memorizing the information and going into his brain to figure out what to do, in which case his searches reveal nothing about cognition.

(Neuroeconomics has an advantage over monitoring search here, because involuntary correlates of such a subject's thinking will still be observable.)

But as we will see, actual searches contain a lot of information about cognition.

With their derived search implications, the types will provide a kind of basis for the enormous space of possible decision and search sequences, imposing enough structure to allow us to describe subjects' behavior in a comprehensible way, and to make it meaningful to ask how decisions and searches are related.

## How Does Cognition Determine Search?

In making additional assumptions about how cognition determines search, the goal is to add enough restrictions to extract the signal from the noise in subjects' look-up sequences; but not so many that they distort the meaning of the signal.

CGC's (and CGCB's) assumptions are conservative in that they rest on types' minimal search implications, and they add as little structure to these as possible.

Types' minimal search implications in CGC's games can be derived from their *ideal guesses*, those they would make if they had no limits. (With automatic rounding of guesses to fall within their limits, and quasiconcave payoffs, this is all they need to know, and all that matters for minimal restrictions on search.)

The left side of Table 4 lists formulas for types' ideal guesses in CGC's games.

The right side lists types' search implications, first in terms of our notation, then in terms of the box numbers in which MouseLab records the data, explained below.

Type	Ideal guess	Relevant look-ups
<i>L1</i>	$p^i [a^i + b^i] / 2$	$\{(a^i, b^i), p^i\} \equiv \{[4, 6], 2\}$
<i>L2</i>	$p^i R(a^i, b^i; p^i [a^i + b^i] / 2)$	$\{(a^i, b^i), p^i, a^i, b^i, p^i\} \equiv \{([1, 3], 5), 4, 6, 2\}$
<i>L3</i>	$p^i R(a^i, b^i; p^i R(a^i, b^i; p^i [a^i + b^i] / 2))$	$\{(a^i, b^i), p^i, a^i, b^i, p^i\} \equiv \{([4, 6], 2), 1, 3, 5\}$
<i>D1</i>	$p^i (\max\{a^i, p^i a^i\} + \min\{p^i b^i, b^i\}) / 2$	$\{(a^i, [p^i, a^i]), (b^i, [p^i, b^i]), p^i\} \equiv \{(4, [5, 1]), (6, [5, 3]), 2\}$
<i>D2</i>	$p^i [\max\{\max\{a^i, p^i a^i\}, p^i \max\{a^i, p^i a^i\}\} + \min\{p^i \min\{p^i b^i, b^i\}, \min\{p^i b^i, b^i\}\}] / 2$	$\{(a^i, [p^i, a^i]), (b^i, [p^i, b^i]), (a^i, [p^i, a^i]), (b^i, [p^i, b^i]), p^i, p^i\} \equiv \{(1, [2, 4]), (3, [2, 6]), (4, [5, 1]), (6, [5, 3]), 5, 2\}$
<i>Eq.</i>	$p^i a^i$ if $p^i p^j < 1$ or $p^i b^i$ if $p^i p^j > 1$	$\{[p^i, p^i], a^i\} \equiv \{[2, 5], 4\}$ if $p^i p^j < 1$ or $\{[p^i, p^i], b^i\} \equiv \{[2, 5], 6\}$ if $p^i p^j > 1$
<i>Soph.</i>	[no closed-form expression, but we take its search implications to be the same as <i>D2</i> 's]	$\{(a^i, [p^i, a^i]), (b^i, [p^i, b^i]), (a^i, [p^i, a^i]), (b^i, [p^i, b^i]), p^i, p^i\} \equiv \{(1, [2, 4]), (3, [2, 6]), (4, [5, 1]), (6, [5, 3]), 5, 2\}$

**CGC's Table 4. Types' Ideal Guesses and Relevant Look-ups**

## Types' Search Implications

Types' search implications are derived as follows.

Evaluating a formula for a type's ideal guess requires a series of *operations*, some of which are *basic* in that they logically precede any other operation.

E.g.  $[a'+b']$  is the only basic operation for  $L1$ 's ideal guess,  $p' [a'+b']/2$ .

The search implications in Table 4 assume that subjects perform basic operations one at a time via adjacent look-ups, remembering their results, and otherwise relying on repeated look-ups rather than memory.

Basic operations will then be represented by adjacent look-up pairs that can appear in either order, but cannot be separated by other look-ups.

Such pairs are grouped within square brackets, as in  $\{[a',b'],p'\}$  for  $L1$ .

Other operations can appear in any order and their look-ups can be separated.

They are represented by look-ups grouped within curly brackets or parentheses.

(Table 4 shows the look-ups associated with a type's operations in the order that seems most natural, if there is one; but this is not a requirement of the theory.)

## Evidence on Cognition and Search

CGCB's and CGC's assumptions how cognition determine search are based on several sources of evidence:

(i) CJ's Robot/Trained Subjects' ("R/TS") searches, which led CJ2 to characterize subgame-perfect equilibrium via backward induction search in terms of transitions between the second- and third-round pies

(ii) CGCB's Trained Subjects' searches, which suggest a similar view of *Equilibrium* search in matrix games

(iii) CGC's R/TS subjects with high compliance with their assigned type's guesses, and CGC's Baseline subjects with high compliance with their apparent type's guesses, whose searches suggest a similar view of *L1* and *L2* search

(CGC's six R/TS treatments were identical to the Baseline except that each subject was trained and rewarded as a type: *L1*, *L2*, *L3*, *D1*, *D2*, or *Equilibrium*.)

(CGC's specification analysis turned up only one clear violation of our proposed characterization of types' search implications: Baseline subject 415, whose apparent type was *L1* with 9 exact guesses, had 0 *L1* search compliance in 9 of the 16 games because s/he had no adjacent  $[a^j, b^j]$  pairs as we required for *L1*. Her/his look-up sequences were unusually rich in  $(a^j, p^j, b^j)$  and  $(b^j, p^j, a^j)$  triples, in those orders. Because the sequences were *not* rich in such triples with other superscripts, this is clear evidence that 415 was an *L1* who happened to be more comfortable with several numbers in working memory than our characterization of search assumes, or than our other subjects were. But because this violated our assumptions on search, this subject was "officially" estimated to be *D1*.)

## Search Data for Representative R/TS and Baseline Subjects

We will now look at some search data for representative R/TS and Baseline subjects from (iii), chosen for high compliance with their type's guesses, not for their compliance with any theory of search.

The data will suggest the following conclusions:

(i) There is little difference between the look-up sequences of R/TS and Baseline subjects of a given type (assigned for R/TS, apparent for Baseline)

(ii) The sequences the theory identifies as relevant for a type (Table 4) are unusually dense in the sequences of subjects of that type, at least for the simpler types (CGC's econometric analysis measures search compliance for a type as the density of its relevant sequences in the subject's look-up sequence)

(iii) One can quickly learn to see the algorithms many subjects are using in the data. (And if we can do it, the right kind of econometrics can do it too: many of CGC's subjects' types can be reliably identified from search alone (Table 7))

(iv) For some subjects search is an important check on decisions; e.g. Baseline subject 309, with 16 exact  $L2$  guesses, misses some of  $L2$ 's relevant look-ups, avoiding deviations from  $L2$  only by luck (even without feedback, s/he later has a Eureka! moment between games 5 and 6, and from then on complies perfectly)

(This is reminiscent of CJ's finding that in their alternating-offers bargaining games, 10% of the subjects *never* looked at the last-round pie and 19% never looked at the second-round pie. Even if those subjects' offer and acceptance decisions had conformed to subgame-perfect equilibrium, they could not have been making equilibrium decisions for the reasons the theory assumes, and we should not expect their equilibrium compliance to persist in a non-magical world.)

Now for the data, but first....

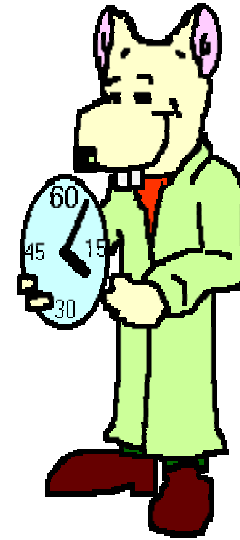
# SPEAK RODENT LIKE A NATIVE IN ONE EASY LESSON!

	LOWER LIMIT	TARGET	UPPER LIMIT
Your Limits&Target	100 +		
HerHis Limits&Target			

Enter your guess (a number from 0 to 1000).

Keyboard Input:

Enter this box and click a mouse button when you are ready.



	<i>a</i>	<i>p</i>	<i>b</i>
You ( <i>i</i> )	1	2	3
S/he ( <i>j</i> )	4	5	6

## MouseLab Box Numbers

# Selected R/TS Subjects' Information Searches and Assigned Types' Search Implications

MouseLab box numbers			
	<i>a</i>	<i>p</i>	<i>b</i>
<b>You (<i>i</i>)</b>	1	2	3
<b>S/he (<i>j</i>)</b>	4	5	6

Types' Search Implications	
<i>L1</i>	{[4,6],2}
<i>L2</i>	{([1,3],5),4,6,2}
<i>L3</i>	{([4,6],2),1,3,5}
<i>D1</i>	{(4,[5,1], (6,[5,3]),2}
<i>D2</i>	{(1,[2,4]),(3,[2,6]),(4,[5,1]),(6,[5,3]),5,2}
<i>Eq</i>	{[2,5],4} if pr. tar.<1, {[2,5],6} if > 1

Subject	904	1716	1807	1607	1811	2008	1001	1412	805	1601	804	1110	1202	704	1205	1408	2002
Type(#rt.)	L1 (16)	L1 (16)	L1 (16)	L2 (16)	L2 (16)	L2 (16)	L3 (16)	L3 (16)	D1 (16)	D1 (16)	D1 (3)	D2 (14)	D2 (15)	Eq (16)	Eq (16)	Eq (15)	Eq (16)
Alt.(#rt.)																	
Est. style	late	often	early	often	early				early								
Game																	
<b>1</b>	123456 4623	146462 134646 23	462513	135462 1313	134446 5213*4 6	111313 131313 5423	462135 21364* 246231 52	146231 564623 1	154356 423213 2642	254514 36231	154346 5213	135464 2646*1 313	246466 135464 641321 342462 422646 124625 5*1224 654646	123456 363256 565365 626365 652651 452262 6526	424652 562525 6352*4 65	632132 11 631454 213452	123123 456445 361454 613451 213452 63
<b>2</b>	123456 4231	462462 13	462132 25	135461 354621 3	134653 125642 313562 52	131313 566622 333 2562*6	462135 642562 223146 2562*6 2	462462 546231	514535 615364 23	514653 6213	515135 365462 3	135134 642163 451463 211136 414262 135362 *14654 6	123645 132462 426262 241356 462*13 524242 466135 6462	635256 212554 146662 456 44526* 31	212554 1 625656	143625 361425 142523 625656 3	

The subjects' frequencies of making their assigned types' (and when relevant, alternate types') exact guesses are in parentheses after the assigned type. A \* in a subject's look-up sequence indicates that the subject entered a guess there without immediately confirming it.

## Selected Baseline Subjects' Information Searches and Estimated Types' Search Implications

MouseLab box numbers			
	<i>a</i>	<i>p</i>	<i>b</i>
<b>You (<i>i</i>)</b>	1	2	3
<b>S/he (<i>j</i>)</b>	4	5	6

Types' Search Implications	
<i>L1</i>	{[4,6],2}
<i>L2</i>	{([1,3],5),4,6,2}
<i>L3</i>	{([4,6],2),1,3,5}
<i>D1</i>	{(4,[5,1], (6,[5,3]),2}
<i>D2</i>	{(1,[2,4]),(3,[2,6]),(4,[5,1]),(6,[5,3]),5,2}
<i>Eq</i>	{[2,5],4} if pr. tar.<1,{[2,5],6} if > 1

Subject	101	118	413	108	206	309	405	210	302	318	417	404	202	310	315
Type(#rt.)	L1 (15)	L1 (15)	L1 (14)	L2 (13)	L2 (15)	L2 (16)	L2 (16)	L3 (9)	L3 (7)	L1 (7)	Eq (8)	Eq (9)	Eq (8)	Eq (11)	Eq (11)
Alt.(#rt.)								Eq (9)	Eq (7)	D1 (5)	L3 (7)	L2 (6)	D2 (7)		
Alt.(#rt.)								D2 (8)			L2 (5)		L3 (7)		
Est. style	early/late	early	late	early	early		early	early	early	early	early	early	early	early/late	early
Game															
<b>1</b>	146246 213	246134 626241 32*135	123456 545612 3463*	135642	533146 213	1352	144652 313312 546232 12512	123456 213456 213213 254213 654	221135 465645 213213 45456*	132456 465252 13242*	252531 464656 446531 641252 462121 3	462135 464655 645515 21354*	123456 254613 621342 *525	123126 544121 565421 254362 *21545 4*	213465 624163 564121 325466
<b>2</b>	46213	246262 2131	123564 62213*	135642 3	531462 31	135263 1526*2 *3	132456 253156 456545 463123 156562 62	123456 465562 231654 456*2 54123	213546 566213 545463 21*266	132465 132*46 2	255236 62*365 243563	462461 352524 261315 463562	123456 445613 255462 513565 23	123546 216326 231456 *62	134652 124653 656121 3
<b>3</b>	462*46	246242 466413 *426	264231	135642 53	535164 2231	135263	312456 5231*1 236545 5233** 513	123455 645612 3 563214 563214 523*65 4123	265413 232145 563214 563214	134652 1323*4 5263*6 52	521363 641526 *52	462135 215634 *52 3	123456 123562 3	123655 463213	132465 544163 *3625

## **CGC's Analysis of Guesses and Search**

In CGC's econometric analysis of guesses and search, most subjects' type estimates reaffirm the guesses-only estimates.

For some subjects the guesses-and-search type estimate resolves a tension between guesses-only and search-only estimates in favor of a type other than the guesses-only estimate.

In more extreme cases, a subject's guesses-only type estimate is excluded because it has 0 search compliance in 8 or more games, like subject 415.

Overall, the incorporating search into the econometric analysis refines and sharpens our conclusions, and confirms the absence of significant numbers of subjects of types other than *L1*, *L2*, *Equilibrium*, or hybrids of *L3* or *Equilibrium*.

## What Else is Search Good for?

To better illustrate the possibilities for search analysis, I now discuss puzzles raised by CGC's analysis, which will be addressed in our sequel, "Studying Cognition via Information Search in Two-Person Guessing Game Experiments."

### **Puzzle a. What are Those Baseline *Equilibrium* Subjects Really Doing?**

Consider CGC's 8 Baseline subjects with near-*Equilibrium* fingerprints.

Ordering the games by strategic structure, with CGC's 8 games with mixed targets (one  $> 1$ , one  $< 1$ ) on the right, shows that their deviations from equilibrium almost always occur with mixed targets (Figure 4).

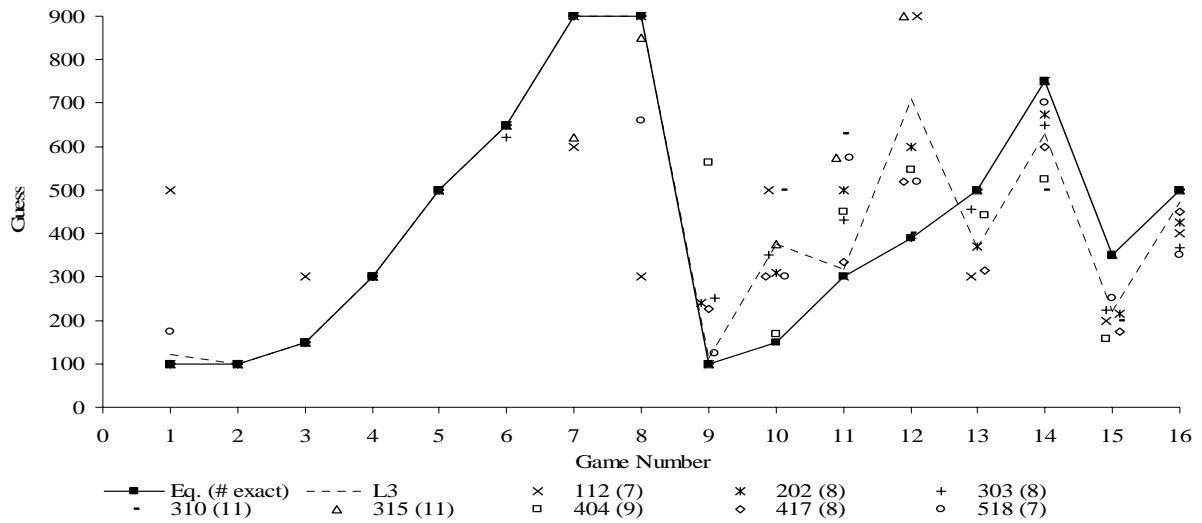
Thus it is (nonparametrically) clear that these subjects, whose compliance with *Equilibrium* guesses is off the scale by normal standards, are actually following a rule that only mimics *Equilibrium*, and that only in games without mixed targets.

Yet all the ways we teach people to identify equilibria (best-response dynamics, equilibrium checking, iterated dominance) work just as well with mixed targets.

Thus whatever these Baseline *Equilibrium* subjects are doing, it's something we haven't thought of yet. (And their debriefing questionnaires don't tell us what it is.)

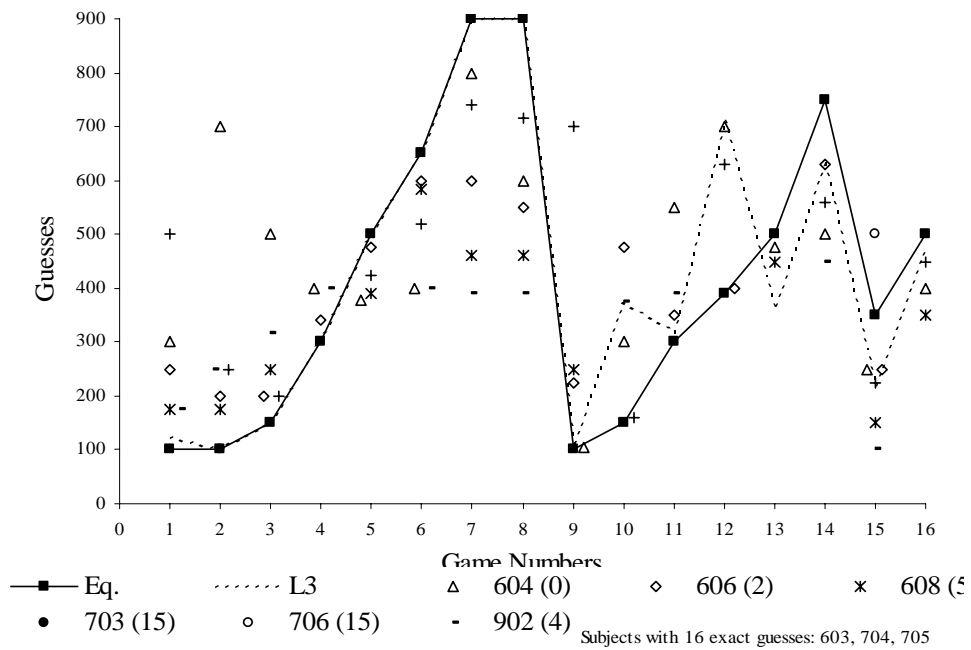
By contrast, CGC's *Equilibrium* R/TS subjects' compliance is equally high with and without mixed targets. (Those subjects were taught to identify equilibria.)

(Remarkably, *all* 44 of our apparent *Equilibrium* subjects' deviations from *Equilibrium* (solid line) when it is separated from *L3* (dotted line), with or without mixed targets, are in the direction of (and sometimes beyond) *L3* guesses. This could reflect the fact that in CGC's games, *L3* guesses are always less extreme.)



**CGC's Figure 4. "Fingerprints" of 8 Apparent Baseline *Equilibrium* Subjects**

**Fingerprints of 10 UCSD Equilibrium R/TS Subjects**  
(only deviations from Eq.'s guesses are shown)



## Possible sources of answers

(i) Can we tell how Baseline *Equilibrium* subjects find equilibrium in games without mixed targets: best-response dynamics, equilibrium checking, iterated dominance, or something else that doesn't "work" with mixed targets?

(The absence of Baseline *Dk* subjects suggests that they are not using iterated dominance. Best-response dynamics, perhaps truncated after 1-2 rounds, seems more likely to us. We can check by refining CGC's characterization of *Equilibrium* search and redoing the econometrics, separately with and without mixed targets.)

(ii) Is there any identifiable difference in Baseline *Equilibrium* subjects' search patterns in games with and without mixed targets? If so, how do the differences compare to those for *L1*, *L2*, or *L3* subjects?

(Our 20 apparent Baseline *L1* subjects' compliance with *L1* guesses (CGC, Figure 1) is almost the same with and without mixed targets: unsurprisingly because the distinction is irrelevant to *L1*. But our 12 apparent *L2* (Figure 2) and 3 apparent *L3* subjects' compliance with apparent types' guesses is noticeably lower with mixed targets. This is curious, because for *L2* and *L3*, unlike for *Equilibrium*, games with mixed targets require no deeper understanding.)

(iii) Can we tell how R/TS *Equilibrium* subjects with high compliance manage to find their *Equilibrium* guesses even with mixed targets? How does their search in those games differ from Baseline *Equilibrium* subjects' search?

(CGC strove to make the R/TS *Equilibrium* training as neutral as possible, but something must come first. We taught them equilibrium checking first, then best-response dynamics, then iterated dominance. To the extent that they used one of those methods, it explains why they have equal compliance with mixed targets. If they used something else, and it deviates from equilibrium in games with mixed targets, it might provide a clue to what the Baseline *Equilibrium* subjects did.)

(Note that CGC's Baseline subjects with high compliance for some type are, to the extent that we are confident in inferring their beliefs, like robot *untrained* subjects. These don't usually exist because you can't tell robot subjects how they will be paid without teaching them how the robot works, and so training them.)

Thus CGC's design provides an unusual opportunity to separate the effects of training and strategic uncertainty, by comparing Baseline and R/TS subjects: Either *Equilibrium* is natural with mixed targets, but subjects don't see it without training; or *Equilibrium* is unnatural, and/or subjects don't believe that others, even with training, will make *Equilibrium* guesses with mixed targets.)

**Puzzle b. Why are *Lk* the only types other than *Equilibrium* with nonnegligible frequencies?**

CGC's analysis of decisions and search revealed significant numbers of subjects of types *L1*, *L2*, *Equilibrium* (with the qualifications expressed above), or hybrids of *L3* and/or *Equilibrium*, and nothing else.

(More precisely, a careful analysis of the data reveals no other types that do better than a random model of guesses for more than one subject.)

Why do these decision rules predominate, out of the enormous number of possible non-equilibrium rules?

(Why, for instance, don't we get *Dk* rules, which are closer to what we teach?)

## Possible sources of answers

Most R/TS subjects could reliably identify their type's guesses, even *Equilibrium* or *D2*. (These average rates are for exact compliance, so quite high. Individual subjects' compliance was usually bimodal within type, on very high and very low.)

**R/TS Subjects' Exact Compliance with Assigned Type's Guesses**

	<i>L1</i>	<i>L2</i>	<i>L3</i>	<i>D1</i>	<i>D2</i>	<i>Eq.</i>
<b>Number of subjects</b>	25	27	18	30	19	29
<b>% Compliance Passed UT2</b>	80.0	91.0	84.7	62.1	56.6	70.3
<b>% Failed UT2</b>	0.0	0.0	0.0	3.2	5.0	19.4

But there are noticeable signs of differences in difficulty across types:

(i) No one ever failed an *Lk* Understanding Test, while some failed the *Dk* and many failed the *Equilibrium* Understanding Tests.

(ii) For those who passed, compliance was highest for *Lk* types, then *Equilibrium*, then *Dk* types. This suggests that *Dk* is even harder than *Equilibrium*, but could just be an artifact of the more stringent screening of the *Equilibrium* Test.

(iii) Among *Lk* and *Dk* types, compliance was higher for lower *k* as one would expect, except that *L1* compliance was lower than *L2* or *L3* compliance.

(We suspect that this is just because *L1* best responds to a random *L0* robot, which some subjects think they can outguess; while *L2* and *L3* best respond to a deterministic simulated *L1* or *L2* robot, which doesn't invite "gambling" behavior.)

(iv) Remarkably, 7 of our 19 R/TS *D1* subjects passed the *D1* Understanding Test, in which *L2* answers are wrong; and then "morphed" into *L2*s when making their guesses, significantly reducing their earnings.

(Recall that it is *L2* that is *D1*'s cousin; these subjects seem to have intuited this.)

E.g. R/TS *D1* subject 804 made 16 exact *L2* (and so only 3 exact *D1*) guesses.

This kind of morphing, in this direction, is the only kind that occurred.

We view this as pretty compelling evidence that *Dk* types are unnatural.

However, a comparison of *Lk*'s and *Dk-1*'s search and storage requirements may have something to add. (E.g. *Dk-1* requires more memory than *Lk*.)

## **A "Theory" of Optimal Search for Hidden Payoff Information**

I now sketch a simple model of optimal search with costs of storing numbers in working memory, which rationalizes the stylized facts of search behavior in CJ's extensive-form and CGCB's and CGC's normal-form experiments.

The model views search for hidden payoff information as just another kind of decision, and takes the formula that relates a type's desired decisions to the hidden parameters as given. In this view, a subject's type determines both an optimal search pattern and an optimal decision.

(As usual, because information has no direct payoff consequences, subjects' demand for it is "derived" from the benefits of making better decisions.)

### **Occurrence**

The usual rationality assumption implies that a player will look up all costlessly available information that might affect his beliefs and best respond to his beliefs.

When, as here, observing a parameter will normally cause a nonnegligible change in beliefs and the optimal decision, this conclusion extends to all relevant information that is available at a sufficiently small but non-0 cost.

(There is a lot of evidence that subjects perceive the cost of a look-up as close to negligible. They look up 50 to 100 payoffs in CGCB's 2x2 matrix games, where at most 8 look-ups would suffice. And they repeat look-ups with few in between.)

Thus, if a type's decision depends on a hidden parameter, then that parameter must appear in the type's look-up sequence. But so far any order will do.

## Adjacency

I further assume that there is a cost of keeping numbers in working memory, which starts out small, but is much larger, even for one number, than the cost of a look-up; and that this cost increases with the number of stored numbers and is proportional to storage time. (Thus a player's "lifetime" total memory cost is the time integral of an increasing function of the number of stored numbers.)

(There is some evidence for these assumptions too.)

Given these assumptions, a player minimizes his total memory plus look-up cost for evaluating an expression like  $L1$ 's ideal guess,  $p^i [a^i + b^i]/2$ , containing a basic operation like  $[a^i + b^i]$ , by processing  $[a^i + b^i]$  separately, storing the result (in the meanwhile "forgetting"  $a^i$  and  $b^i$ ), and combining the result with  $p^i$ .

(The alternative, processing  $p^i a^i$  separately, storing the result, then processing  $p^i b^i$  separately and combining it with  $p^i a^i$ , requires leaving more numbers in working memory longer: The sequence of numbers in memory for the method in the previous paragraph is 1, 2, 1, 2, 1; the sequence for the method in this paragraph is 1, 2, 1, 2, 3, 2, 1. The previous method also saves by eliminating the repeated look-up of  $p^i$ , but this is of second-order importance.)

I have only illustrated the cost savings from giving priority to basic operations, but I conjecture that the argument is general. If so, it justifies assuming that subjects perform basic operations one at a time via adjacent look-ups, remembering the results, and otherwise relying on repeated look-ups rather than memory.

The argument also seems likely to extend to CJ's extensive-form games, justifying their focus on transitions between pies from adjacent rounds.

The theory implies more than this, regarding both the order of operations (basic ones should come first) and how non-basic operations are executed. I defer such implications in favor of mentioning an issue regarding CGC's search data:

Many Baseline subjects usually look first at their apparent type's relevant sequence and then make irrelevant look-ups or stop (e.g. 108, 118, and 206, labeled "early" in the above look-up data). Others make irrelevant look-ups first, and look at the relevant sequence only near the end (e.g. 413, labeled "late"). Others repeat the relevant sequence many times (e.g. 101, labeled "early/late"). The theory is actually consistent with this kind of heterogeneity when look-up costs are negligible (but storage costs are not). Because MouseLab allows a subject to enter a tentative guess without confirming it (the \*s in the look-up data), this kind of storage has zero cost in CGC's and CGCB's designs; and so subjects can satisfy their curiosity (early or late) without running up storage costs.

## **Appendix: Camerer and Johnson's Backward-Induction Experiments and Costa-Gomes, Crawford, and Broseta's Matrix-Game Experiments**

In CJ1 and CJ2, subjects played series of two-person, three-round alternating-offers bargaining games in which the "pie" varies across rounds to simulate discounting at a common rate, with different partners and pies each round.

Previous experiments yielded large, systematic deviations from the subgame-perfect equilibrium offer and acceptance decisions when players have purely pecuniary preferences (like those usually observed in ultimatum experiments).

Such deviations had been attributed to cognitive limitations that prevent subjects from doing backward induction (or believing others will) or to subjects having social preferences, or both. The relative importance of these factors was unclear.

CJ's innovation was to create a design that made it possible to study the cognitive underpinnings of behavior via search as well as decisions.

Their design replicated previous results in a way that allowed a more precise assessment of cognition, which suggested limited cognition was more significant than previously thought (but social preferences were also an important factor).

### **Monitoring Search via MouseLab in Alternating-Offers Bargaining Games**

Within a publicly announced extensive-form structure, each game was presented to subjects as a series of pies via MouseLab, which normally concealed the pies but allowed subjects to look them up as often as desired, one at a time (rollover option in MouseLab). (Subjects could also look up their roles in each round; but these were known and such look-ups were not analyzed.)

(Subjects were not allowed to write down the pies, and the frequencies with which they looked them up made clear that they did not memorize them.)

The design allowed subjects to evaluate their own and their partners' pecuniary payoffs for any decision combination, and to combine this evaluation with their own assessment of their partners' distribution of social preferences.

The representation of payoffs as functions of a small number of hidden payoff parameters within a publicly announced structure is a strength of CJ's design, which allows subjects to focus on predicting their partners' responses while yielding good separation of the search implications of alternative decision rules.



**CJ2's Figure 1. MouseLab Computer Display**

### Separation of Types' Implications for Decisions in CJ's Design

Like other designs whose goal is studying strategic thinking, CJ's separates the decisions implied by alternative types, making it possible to discriminate among alternative types via offer and acceptance decisions alone.

Focusing on players' offers as initial proposer (CJ's design also separates responders' acceptance cut-offs), the leading types are as follows:

CJ2's *Equilibrium* type offers (approximately) \$1.25, the subgame-perfect equilibrium offer when players have pecuniary preferences and the structure is public knowledge.

CJ2's *Level-1* type offers (approximately) \$1.50, the expected-payoff maximizing offer looking one round ahead, on the assumption that the other player will offer 40% of the remaining pie in the second round, as is usually observed in ultimatum experiments. (Thus *Level-1* is less far-sighted than *Equilibrium*, but subject to this limitation it is a better behavioral game theorist.)

CJ2's *Level-0* type offers (approximately) \$2.00, 40% of the first-round pie. (*Level-0* is completely myopic, but still an optimizing behavioral game theorist.)

One might add a *Fair* (and efficient) type that offers \$2.50, 50% of the first-round pie.

## Separation of Types' Implications for Search in CJ's Design

CJ's design also makes it possible to test and compare alternative theories via search, even (at least in principle) without observing subjects' decisions.

If players have pecuniary preferences and the structure is otherwise public knowledge, CJ's games have unique subgame-perfect equilibria, in which players' offer and acceptance decisions are dictated by the pies.

If players have privately observed social preferences but the structure is otherwise public knowledge, CJ's games have generically unique sequential equilibria, in which players' offer and acceptance decisions are influenced (though not dictated) by the pies.

In each case the equilibria are easy to compute by backward induction.

Both CJ's *Equilibrium* type and its sequential equilibrium analog with social preferences (defined along the lines of CJ's *Level-1* type) make offer and acceptance decisions that depend on the second- and third-round pies.

(Without social preferences, *Equilibrium*'s decisions are independent of the first-round pie. With social preferences, the first-round pie may also be relevant, because it may then influence the responder's acceptance decision.)

*Level-1*'s initial offer does not depend on the third-round pie.

(Without social preferences, *Level-1*'s initial offer depends only on the second-round pie. With social preferences the first-round pie may again be relevant.)

*Level-0*'s and *Fair*'s initial offers depend only on the first-round pie, because *Level-0*'s model of the responder is independent of later pies and *Fair* doesn't even have a model.

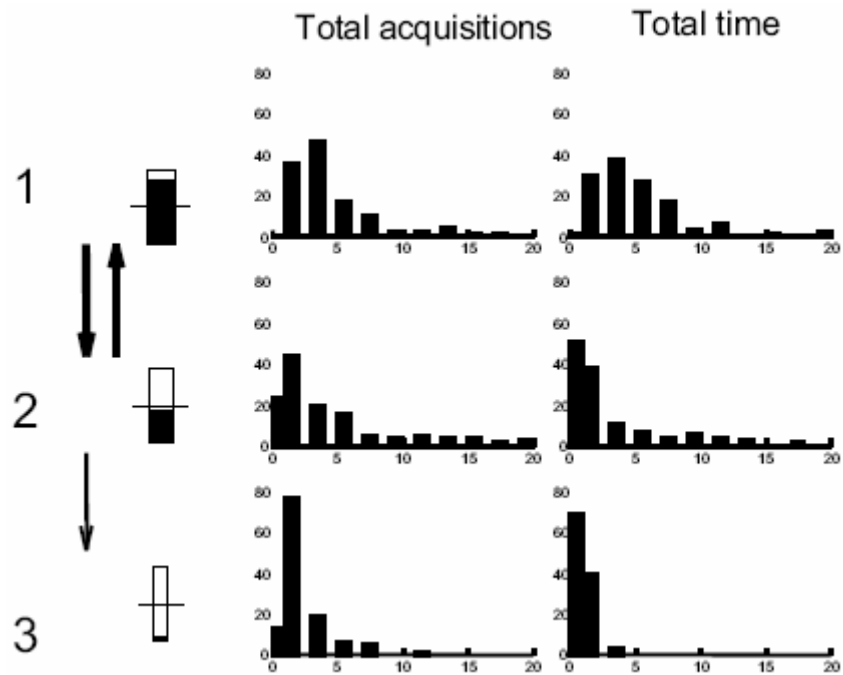
The fact that CJ's design strongly and independently separates leading alternative theories' implications for both decisions and search is another important strength.

Subjects' searches and decisions together yield a clearer view of behavior than is possible studying either in isolation.

## CJ's Results

CJ2's Baseline subjects (untrained and rewarded for their payoffs playing against each other) looked most often and longest at the first-round pie, with most transitions forward rather than backward.

10% *never* looked at the last-round pie and 19% never looked at the second-round pie. Even if those subjects' decisions conform to the equilibrium, they cannot be choosing those decisions for the reasons the theory assumes, and we should not expect their equilibrium compliance to persist in a non-magical world.



**CJ2's Figure 3. Icon Graphs and Histograms of Acquisitions and Looking Time (Baseline Treatment)**

This much is uncontroversial, but the insight it yields is limited.

To realize the full power of monitoring search, we must go beyond observing that subjects' behavior cannot be (reliably) related to information they do not have.

This requires assumptions about how cognition drives search that go beyond those that we have been socialized to accept.

(Without further assumptions, it is logically possible for a subject to look up the pies in any order, memorize them, and then "go into his brain" to figure out what to do. If he does this, his searches will reveal nothing about cognition. Neuroeconomics has a potential advantage over search here, because involuntary correlates of such a subject's thinking will still be observable.)

Fortunately, CJ's subjects' searches had strong regularities that can be used to infer cognition from search.

CJ argued that the backward induction associated with their *Equilibrium* type has a characteristic search pattern, in which subjects look most often at the last- and second-round pies, with most transitions backward rather than forward.

In other words, almost the perfect opposite of what their Baseline subjects did!

When CJ's characterization of backward induction search was challenged, they supported their claim empirically by a Robot/Trained Subjects treatment, with subjects trained in backward induction (but not search strategies) and told (in plainer language) that they played against a computer programmed to follow its (self-interested, money-maximizing) subgame-perfect equilibrium strategy.

(CJ also argued that their R/TS treatment disables social preferences, whose importance can then be estimated by comparing its results with the Baseline.)

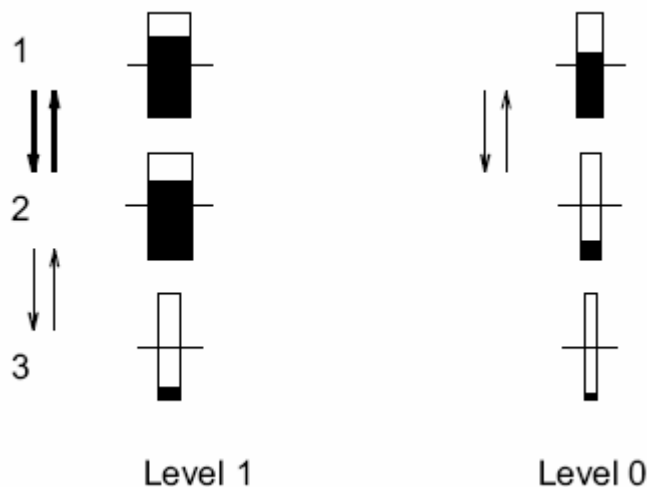
Unlike CJ's Baseline subjects, who deviated strongly from the backward-induction search pattern, CJ's R/TS subjects came reasonably close to the pattern, while making decisions close to the subgame-perfect equilibrium.

Further, as can be seen (to some extent) in CJ2's Figure 4, subjects who tended to make offers closer to the subgame-perfect equilibrium also had search patterns closer to what CJ argued was the backward induction pattern.

Subjects who tended to make acceptance decisions closer to the subgame-perfect equilibrium also had search patterns closer to backward induction.

In other words, given CJ's metrics, subjects' deviations from subgame-perfect equilibrium in decisions and search were correlated, in the "right" direction.

This fascinating result foreshadows the power of studying cognition via search.



**CJ2's Figure 4. Icon graphs for initial proposer type inferred from first-round offer**

**(there were no *Equilibrium* subjects in the baseline)**

**(width of arrow = transition frequency; width of box = number of look-ups; height of shaded part of box = total gaze time)**

## **Costa-Gomes, Crawford, and Broseta's Matrix-Game Experiments**

CGCB (inspired by CJ1 but written before CJ2's analysis took its final form) adapted CJ's methods to study cognition via search for hidden payoffs in matrix games, eliciting initial responses to 18 games with various patterns of iterated dominance or unique pure-strategy equilibria without dominance (Figure 2).

CGCB's design strongly separates leading types' implications for decisions.

Previous experiments (e.g. Stahl and Wilson, *Games and Economic Behavior* 1995) found systematic deviations from the equilibrium decisions when players have pecuniary preferences (in games that probably disable social preferences).

CGCB's results for decisions replicated most patterns in previous experiments, with high equilibrium compliance with in games solvable by one or two rounds of iterated dominance but lower compliance in games solvable by three rounds or by the circular logic of equilibrium without dominance (Table II).

CGCB's design replicated previous results in a way that allowed a more precise assessment of subjects' cognition, which confirms the view of subjects' behavior suggested by analyses of decisions alone, with some differences.

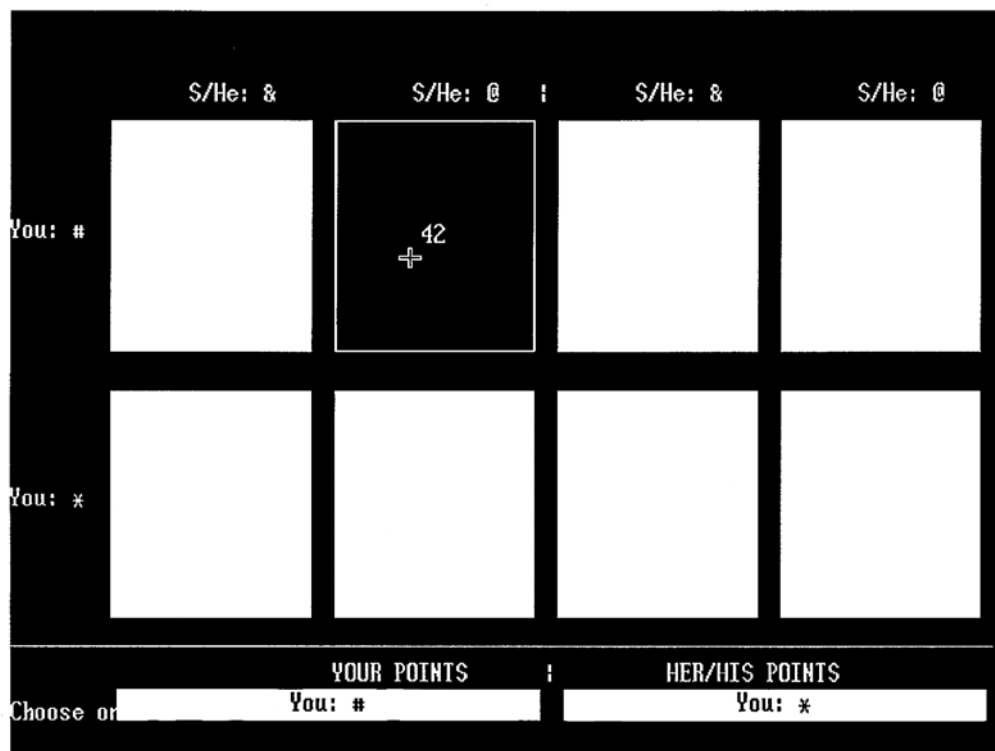
## Monitoring Search via MouseLab in Matrix Games

Within a publicly announced structure, CGCB presented each game to subjects as a matrix via MouseLab, which normally concealed payoffs but allowed subjects to look up their own and their partner's payoffs for each decision combination as often as desired, one at a time (click option in MouseLab).

Row and Column players' payoffs were spatially separated to ease cognition and make search more informative.

(Subjects were always framed as Row players, although each played each of our games once as Row and once as Column player, in a sequence that disguised those relationships and randomized away effects of patterns in their structures.)

(Subjects were not allowed to write down the payoffs, and the frequencies with which they looked them up made clear that they did not memorize them.)



**CGCB's Figure 1. MouseLab Screen Display (for a 2x2 game)**

**Separation of Types' Implications for Decisions in CGCB's Design: Figure 2**

2A (1,2)	A,P,N	D12,L2,E,S
A	72,93	31,46
D	84,52	55,79

2B (1,2)	A,P,N	D12,L2,E,S
D	94,23	38,57
A	45,89	14,18

3A (2,1)	D	A
D12,L2,E,S	75,51	42,27
A,P,N	48,80	89,68

3B (2,1)	D	A
A,P,N	21,92	87,43
D12,L2,E,S	55,36	16,12

4A (2,1)	D	A	
A,P,N	59,58	46,83	85,61
D12,L2,E,S	38,29	70,52	37,23

4B (2,1)	A	D
D12,L2,E,S	31,32	68,46
P	72,43	47,61
A,N	91,65	43,84

4C (1,2)	D12,L2,E,S	A,P,N
A	28,37	57,58
D	22,36	60,84
D	51,69	82,45

4D (1,2)	D12,L2,E,S	P	A,N
D	42,64	57,43	80,39
A	28,27	39,68	61,87

5A (3,2)	A,P,N	D12,L2,E,S
A	53,86	24,19
P,N,D1,L2,S	79,57	42,73
D2,E	28,23	71,50

5B (3,2)	A,P,N	D12,L2,E,S
A	76,93	25,12
D2,E	43,40	74,62
P,N,D1,L2,S	94,16	59,37

6A (2,3)	A	D2,E,S	P,N,D1,L2
D12,L2,E,S	21,26	52,73	75,44
A,P,N	88,55	25,30	59,81

6B (2,3)	D2,E	A	P,N,D1,L2,S
A,P,N	42,45	95,78	18,96
D12,L2,E,S	64,76	14,27	39,61

7A ( $\infty, \infty$ )	N,D12,L2,S	A,P	E
L2,E,S	87,32	18,37	63,76
A,P,N,D12	65,89	96,63	24,30

7B ( $\infty, \infty$ )	N,D12,L2,S	A,P	E
A,P,N,D12	67,91	95,64	31,35
L2,E,S	89,49	23,53	56,78

8A ( $\infty, \infty$ )	L2,E,S	A,P,N,D12
E	72,59	26,20
A,P	33,14	59,92
N,D12,L2,S	28,83	85,61

8B ( $\infty, \infty$ )	L2,E,S	A,P,N,D12
A,P	46,16	57,88
E	71,49	28,24
N,D12,L2,S	42,82	84,60

9A (1,2)	D12,L2,E,S	A,P,N
A	22,14	57,55
D	30,42	28,37
A	15,60	61,88
D	45,66	82,31

9B (2,1)	A	D		
A,P,N	56,58	38,29	89,62	32,86
D12,L2,E,S	15,23	43,31	61,16	67,46

(A = Altruistic, P = Pessimistic (minimax), N = Naïve (CGCB's name for L1) and Optimistic (maximax, decisions not separated from Naïve's), E = Equilibrium, S = Sophisticated, D12 = D1 and D2, D = dominant decision = all types but A.)

## Separation of Types' Implications for Search in CGCB's Design

CGCB's design also makes it possible to test and compare types via search.

They make two assumptions about how cognition affects search, *Occurrence* and *Adjacency* that are close to CGC's characterization of cognition and search.

In CGCB's display, a subject's searches can vary in three main dimensions:

- (i) the extent to which his transitions are up-down in his own payoffs, which under *Occurrence* and *Adjacency* is (for a Row player) naturally associated with rationality in the decision-theoretic sense;
- (ii) the extent to which his transitions are left-right in other's payoffs, which under *Occurrence* and *Adjacency* is associated with thinking about other's incentives;
- (iii) the extent to which he makes transitions from own to other's payoffs and back for the same decision combination, which under *Occurrence* and *Adjacency* is associated with interpersonal fairness or competitiveness comparisons.

This variation allows strong separation of types' implications for search.

The independent separation of types' implications for decisions and search is an important strength of the design: Searches and decisions together, and their relationships, yield a much clearer view of a subject's type than decisions alone.

Some types' implications under *Occurrence* and *Adjacency* in game 3A (Column has dominant decision, "nonstrategic" Rows pick B and "strategic" Rows pick T)

	<b>S/He: L</b>	<b>S/He: R</b>	<b>S/He: L</b>	<b>S/He: R</b>
<b>You: T</b>	<b>75</b>	<b>42</b>	<b>51</b>	<b>27</b>
<b>You: B</b>	<b>48</b>	<b>89</b>	<b>80</b>	<b>68</b>
	<b>Your</b>	<b>Points</b>	<b>Her/His</b>	<b>Points</b>
	<b>You: T</b>		<b>You: B</b>	

*Naïve (L1)* compares expected payoffs of own decisions given a uniform prior over other's, via either up-down or left-right own payoff comparisons. *Occurrence* requires look-ups 75, 48, 42, and 89. *Adjacency* requires either the set of comparisons  $\{(75,42), (48,89)\}$  or the set of comparisons  $\{(75,48), (42,89)\}$ .

	<b>S/He: L</b>	<b>S/He: R</b>	<b>S/He: L</b>	<b>S/He: R</b>
<b>You: T</b>	<b>75</b>	<b>42</b>	<b>51</b>	<b>27</b>
<b>You: B</b>	<b>48</b>	<b>89</b>	<b>80</b>	<b>68</b>
	<b>Your</b>	<b>Points</b>	<b>Her/His</b>	<b>Points</b>
	<b>You: T</b>		<b>You: B</b>	

*L2* needs to identify other's *Naïve* decision and *L2*'s best response to it; Occurrence requires all other's look-ups plus 75 and 48, the own look-ups for other's *Naïve* decision. Adjacency requires either the set of comparisons  $\{(51,27), (80,68)\}$  or the set of comparisons  $\{(51,80), (27,68)\}$  to identify other's *Naïve* decision, plus the comparison (75,48) to identify *L2*'s best response.

If *Equilibrium* has a dominant decision it needs only to identify it. If not, it can use iterated dominance or equilibrium-checking, decision combination by combination or via "best-response dynamics." Occurrence requires look-ups 51, 27, 80, 68, 75, and 48. Adjacency requires comparisons (51,27), (80,68), and (75,48).

## CGCB's Results

The most frequent estimated types are *Naïve* (*L1*) and *L2*, each nearly half of the population.

Incorporating search compliance into the econometric analysis shifts the estimated type distribution toward *Naïve*, at the expense of *Optimistic* and *D1*.

Part of this shift occurs because *Naïve*'s search implications explain more of the variation in subjects' searches and decisions than *Optimistic*'s, which are too unrestrictive to be useful in the sample.

Another part occurs because *Naïve*'s search implications explain more of the variation in subjects' searches and decisions than *D1*'s, which are more restrictive, but too weakly correlated with subjects' decisions.

*D1* also loses some frequency to *L2*, even though their decisions are weakly separated in CGCB's design, because *L2*'s search implications explain much more of the variation in subjects' searches and decisions.

Overall, CGCB's analysis of decisions and search yields a significantly different interpretation of behavior than their analysis of decisions alone. The analysis suggests a strikingly simple view of behavior, with *Naïve* and *L2* 65-90% of the population and *D1* 0-20%, depending on confidence in their model of search.