Artificial Economic Agents with Heterogeneous Cognitive Capacity and Their Economic Consequences: Study Based on Agent-Based Double Auction Market

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Shu-Heng Chen, Chung-Ching Tai, and Lei-Xieng Yang
chchen@nccu.edu.tw, chungching.tai@gmail.com
lxyang@nccu.edu.tw

http://www.aiecon.org/

Research Center of Brain, Mind and Learning

National Chengchi University
Taipei, Taiwan
Outline

- Motivation and Background
- Human-Subject Experiments
- Agent-Based Simulations
- Concluding Remarks
The economic significance of cognitive capacity has recently drawn intensive attention from economists.

On the one hand, empirical studies indicating the significant correlation between cognitive capacity and economic performance has piled up;

On the other hand, experimental economists has started to treat cognitive capacity as a control variable and inquire its economic consequences based on the conducted experiments.
Motivation

- Despite the active publications of cognitive economic experiments since late 1990s, most existing experiments are carried out in the context of games.
- The significance of cognitive capacity in market experiments has, however, rarely been addressed.
- The lack of study in this area, to some extent, echoes with the assumption that the market mechanism is so powerful and robust that it leaves no room to participants' intelligence, learning, and whatsoever.
- This assumption is also well preached as the zero-intelligence-plus (ZIP) hypothesis (Becker, 1962; Gode and Sunder, 1993, 1994).
Motivation

- Nevertheless, this assumption has never been tested in any traditional market experiment.
- Hence, no matter how sound it might be, the ZIP hypothesis is yet to be verified.
- This paper, therefore, provides the first attempt to examine whether the cognitive capacity of subjects can matter in market experiments, and we take double auction markets as our first step, since it was considered as the least likely place that cognitive ability can have an effect.
- So, it serves as a benchmark.
In this paper, we study the significance of the cognitive capacity in the context of double auction experiments. These experiments are then simulated using artificial agents in an agent-based modeling environment, and the results are compared with the results from human subjects.
Background: Economic Significance of Cognitive Capacity (Intelligence)

- Income (Herrnstein and Murray, 1996; Jensen, 1998)
- Labor econometrics (Cawley, 1997; Zax and Rees, 2002; Gould, 2005)
- Wealth of Nations (Lynn and Vanhanen, 2002; Lynn 2006)
- Economic Growth (Weede and Sebastian, 2002; Jones and Schneider, 2006; Ram, 2007)
Cognitive Capacity in Experimental Economics

- Segal and Hershberger (1999): prisoners’ dilemma game
- Devetag and Warglien (2003): dominance-solvable game
- Ohtsubo and Rapoport (2006): beauty contest game
- Casari, Ham and Kagel (2007): common-value auction
- Cornelissen, Dewitte and Warlop (2007): dictator game
- Cappelletti, Guth and Ploner (2008): ultimatum game
- Devetag and Warglien (2008)
- Jones (2008): prisoners’ dilemma game
- Burks, Carpenter, Goette, and Rustichini (2009)
In the human-subject experiment, each subject is placed within a double auction experiment where his/her opponents are all software agents.

To differentiate the complexity of software agents, two kinds of agents are presented:

- **Truth Tellers**
- **Programmed Agents**
  - Program agents are collected from the literature.

We shall call the experiments with truth tellers Exp Series 1, and the experiments with programmed agents Exp Series 2.
Exp Series I was conducted with a sample of 46 subjects, whereas Exp Series II was conducted with a sample of 39 subjects.

Attributed of human subjects are briefly highlighted as follows.

- All subjects are students, either graduate students or undergraduate students.
- Most subjects are inexperienced, i.e., they have little experience in real auction markets, such as the stock markets. Only 13 in the Exp Series I, and 8 in Series II are experienced.

The focusing attribute considered in this paper is the working memory capacity.
Working Memory Test

- All subjects are required to perform a working memory capacity (WMC) test before they can get the monetary reward from the experiments.

- **Five WMC tasks** were used:
  - **Backward Digit Span** (BDG),
  - **Memory Updating** (MU),
  - **Operation Span** (OS),
  - **Sentence Span** (SS), and
  - **Spatial Short-Term Memory** (SSTM).
Working Memory Tests

- By following the conventional procedure in psychological tests, the score of each task are normalized using the mean and the standard deviation of the subject pool.
- The five standardized scores of the five tasks will then be averaged to get the WMC of a specific subject.
- By this procedure, we are able to further classify our human agents into two groups: those whose WMC are above average (18:15) and those whose WMC are below average (18:13).
- This classification will facilitate our analysis.
Demand and Supply Schedule

- Three different demand and supply schedules are used in both Exp Series I and Exp Series II.
- For making comparisons, these three are the same across the two series, and they are shown in this figure.
- Each subject is required to go through all these three markets, denoted by M1, M2, and M3, and for each market six iterations (six trading days).
- Their performance in terms of efficiency indexes are recorded are shown in these figures.
  - In these figures, red lines and blue lines are jumping around and crossing each other.
  - Therefore, it is hard to see whether working memory capacity has an effect on these individuals’ performance.
Experimental Results: Group Average

- We, therefore, turn to compare the average performance of the group with lower memory capacities (the below-average group) with those of the group with higher ones (the above-average group).

- The result is shown in this figure.
  - A quick look at the results seems to indicate that there is a performance difference between the two groups.
  - Subjects whose working memory capacities are above the average tend to perform better than subjects whose working memory capacities are below average.
Experimental Results: Regression

- Alternatively, instead of seeing the group difference, we also examine the capability of the WMC on explaining the performance at an individual level.

- A simple linear regression is proposed to fit the data.

\[ y_{i,6} = \alpha + \beta x_{i,6} + \varepsilon_{i,6} \]

- \( y_{i,6} \): efficiency index of the subject i at period 6
- \( x_{i,6} \): working memory capacity of subject i at period 6
Experimental Results: Regression

- The regression result of the two market series is shown [here](Exp Series I) and [here](Exp Series II).
- The result shows that coefficient of working memory capacity is insignificant in most cases.
- In addition to this one-period snapshot, to examine the possible influence of the WMC on learning, we also trace the correlation of the WMC and the efficiency index in each period, and the result is shown [here](Exp Series II).
Effect of WMC under Learning

- The table shows two possibilities.
  - **Case 1**: The WMC had the initial effect, but then the effect gradually disappeared when all subjects were subjected to learning.
  - **Case 2**: The WMC had little effect even in the initial period.
- The only case which we see that the WMC has a persistent positive effect is Market 3 (M3) of the Exp Series I.
Agent-Based Simulation

- In the case of agent-based simulation, we replace the human agents with autonomous agents, the autonomous agents are modeled with genetic programming.
- To make our agent-based simulation comparable to the human experimental counterpart, we need to make them differ in “cognitive capacity”
- The parameter which we used to manipulate their working memory capacity is the population size, a key parameter of GP.
Agent-Based Simulation

- We consider three different population sizes: 5, 25, and 125.
- These artificial agents with different population size are therefore assumed to match human agents with different working memory capacity.
- These artificial agents are then placed into the same two experimental series with the same three markets used in the human subject experiments.
- The results are shown in this figure.
Simulation Results

- We further apply the Wilcoxon Rank Sum Test to the data, and the results are given in these tables.
- The test shows that cognitive capacity matters only in Market 3 under Simulation Series I, but matters in almost all markets under Simulation Series II.
- Comparing these results with those of human-subjects experiments, we have matches in Series I, but mismatches in Series II.
Concluding Remarks

- An attempt to study the economic significance of the double auction markets is made both in human-subject experiments and agent-based simulation.
- While only weak evidence of the economic significance of cognitive capacity is found in human-subject experiments, our agent-based simulations indicate somewhat stronger association.
Concluding Remarks

- In addition, **human agents perform much better when all opponents are all programmed agents.**
- **They perform even better than what our autonomous agents did.**
- Therefore, finding the incarnation of human agents in terms of software agents remains to be a challenging task.
Human Subject vs Software Agents: EXP Series I

**Market**

- **Token-Value Generation Process**
- **Token-Value Table**
- **Demand and Supply Curves**
  - Market Structure
  - Curves' Shapes
  - Competitive Equilibria

**A Trading Period**

- **Bid-and-Ask**
- **Buy-and-Sell**
- **AURORA**

**Actual Price and Actual Surplus**

**DA Market**
Human Subject vs Software Agents: Exp Series II

[Diagram showing a market with buyers and sellers connected by arrows and labeled as Kaplan, Buyer 1, Buyer 2, Buyer 3, Buyer N1, GD, Ringuette, Seller 1, Seller 2, Seller 3, Seller N2, ZIP, Markup, Skeleton, EL.]
Programmed Agents

- BGAN (Friedman, 1991)
- ZIC (Gode & Sunder, 1993)
- EL (Easley & Ledyard, 1993)
- Skeleton (Rust et al. 1994)
- Kaplan (Rust et al. 1994)
- Ringuette (Rust et al. 1994)
- ZIP (Cliff & Bruten, 1997)
- GD (Gjerstad & Dickhaut, 1998)
- Empirical Bayesian inspired by (Chan, 1999)
- Markup (Zhan & Friedman 2007)
This page gives an overview of my current research interests, with links to publications for download. Supplementary material to Oberauer & Lewandowsky (2008), Psychological Review, can be found here.

Working Memory
- What is working memory capacity?
- Why is working memory capacity limited?
- The architecture of working memory
- Age differences in working memory
- Can we think two things at once?

Reasoning
- Mental models in deductive reasoning
- The meaning of conditionals

Working Memory
What is working memory capacity?

When talking about working memory capacity, we assume that there is one capacity limit underlying many different observed limitations on cognitive performance. Evidence for this contention comes from factor analytic studies showing that many different ways of measuring working memory capacity load on the same or closely related factors.
Market 2
Market 3
### Regression – EXP1

#### Compete with Truth Tellers

<table>
<thead>
<tr>
<th>Model</th>
<th>Estimate</th>
<th>Standard Error</th>
<th>t statistic</th>
<th>p-value</th>
<th>R²</th>
<th>Adjusted R²</th>
</tr>
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<tbody>
<tr>
<td>M1</td>
<td>intercept</td>
<td>93.004</td>
<td>11.280</td>
<td>8.245</td>
<td>2.59e-09</td>
<td>0.001335</td>
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<td></td>
<td>wmc</td>
<td>-3.868</td>
<td>18.996</td>
<td>-0.204</td>
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<td>M2</td>
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<td>87.61</td>
<td>14.79</td>
<td>5.925</td>
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<td>wmc</td>
<td>16.13</td>
<td>24.90</td>
<td>0.648</td>
<td>0.522</td>
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<tr>
<td>M3</td>
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<td>97.924</td>
<td>1.730</td>
<td>56.595</td>
<td>&lt;2e-16</td>
<td>0.1956</td>
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<td>2.914</td>
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### Regression – EXP2

#### Compete with Strategies from the Literature

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<th>Estimate</th>
<th>Standard Error</th>
<th>t statistic</th>
<th>p-value</th>
<th>R²</th>
<th>Adjusted R²</th>
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<tr>
<td><strong>M1</strong></td>
<td>intercept</td>
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<td>wmc</td>
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<tr>
<td><strong>M2</strong></td>
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<td>wmc</td>
<td>-1.659</td>
<td>17.139</td>
<td>-0.097</td>
<td>0.924</td>
<td>-</td>
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<tr>
<td><strong>M3</strong></td>
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<td>126.851</td>
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<td>11.980</td>
<td>9.43e-13</td>
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<td></td>
<td>wmc</td>
<td>3.019</td>
<td>17.384</td>
<td>0.174</td>
<td>0.863</td>
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## Correlation Coefficient between the WMC and the Efficient Index

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<th>Period</th>
<th>EXP1_M1</th>
<th>EXP1_M2</th>
<th>EXP1_M3</th>
<th>EXP2_M1</th>
<th>EXP2_M2</th>
<th>EXP2_M3</th>
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<td>1</td>
<td>0.21</td>
<td>0.27</td>
<td>0.24</td>
<td>0.25</td>
<td>0.07</td>
<td>-0.18</td>
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<td>2</td>
<td>0.25</td>
<td>0.18</td>
<td>0.12</td>
<td>-0.01</td>
<td>-0.14</td>
<td>-0.07</td>
</tr>
<tr>
<td>3</td>
<td>0.21</td>
<td>0.17</td>
<td>0.52</td>
<td>-0.27</td>
<td>0.06</td>
<td>-0.04</td>
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<tr>
<td>4</td>
<td>0.17</td>
<td>0.11</td>
<td>0.40</td>
<td>0.08</td>
<td>0.10</td>
<td>0.07</td>
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<tr>
<td>5</td>
<td>0.20</td>
<td>0.20</td>
<td>0.54</td>
<td>0.06</td>
<td>0.09</td>
<td>0.10</td>
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<tr>
<td>6</td>
<td>-0.04</td>
<td>0.12</td>
<td>0.44</td>
<td>-0.01</td>
<td>-0.02</td>
<td>0.03</td>
</tr>
</tbody>
</table>
Human Subject vs Software Agents: EXP Series I

DA Market
Token-Value Generation Process
Token-Value Table
Demand and Supply Curves
Market Structure
Curves' Shapes
Competitive Equilibria
Total Surplus = Consumers' + Producers' Surplus

A Trading Period
Bid-and-Ask
Buy-and-Sell
AURORA
S-Step Loop
Actual Price and Actual Surplus

Buyer 1
Buyer 2
Buyer 3
Buyer N₁
Seller 1
Seller 2
Seller 3
Seller N₂

T.T
GP
T.T
T.T
T.T
Human Subject vs Software Agents: Exp Series II

Market

Demand and Supply Curves
- Market Structure
- Curves' Shapes
- Competitive Equilibria

Total Surplus = Consumers' + Producers' Surplus

A Trading Period
- Bid-and-Ask
- Buy-and-Sell
- AURORA

Actual Price and Actual Surplus

Token-Value Generation Process

Token-Value Table

A Trading Step
- S-Step Loop

DA

Buyer 1
- Kaplan

Buyer 2
- GP

Buyer 3
- GD

Buyer N1
- Ringuette

Seller 1
- ZIP

Seller 2
- Markup

Seller 3
- Skeleton

Seller N2
- EL
SIM1
SIM2
<table>
<thead>
<tr>
<th></th>
<th>P5</th>
<th>P25</th>
<th>P125</th>
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</thead>
<tbody>
<tr>
<td>P5</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P25</td>
<td>M1 0.2168</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>M2 0.3690</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>M3 0.004758**</td>
<td></td>
<td></td>
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<tr>
<td>P125</td>
<td>M1 0.1416</td>
<td>M1 0.3660</td>
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<td></td>
<td>M2 0.003733**</td>
<td>M2 0.1467</td>
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<td></td>
<td>M3 0.00000007873**</td>
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</tr>
<tr>
<td></td>
<td>P5</td>
<td>P25</td>
<td>P125</td>
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<td>-------</td>
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<td>--------------------</td>
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<tr>
<td>P5</td>
<td>X</td>
<td></td>
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</tr>
<tr>
<td>P25</td>
<td>M1 5.538e-07**</td>
<td>M2 0.3778</td>
<td>M3 0.004683**</td>
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<tr>
<td>P125</td>
<td>M1 2.82e-16**</td>
<td>M1 0.0009483**</td>
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<td></td>
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<td>M2 0.006392**</td>
<td>M3 0.07213*</td>
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<td></td>
<td>M3 8.201e-06**</td>
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## Human vs. Programmed Agents

<table>
<thead>
<tr>
<th></th>
<th>Human</th>
<th>Kaplan</th>
<th>GD</th>
<th>ZIP</th>
<th>Skeleton</th>
<th>EL</th>
<th>Markup</th>
<th>Ringuette</th>
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<tbody>
<tr>
<td>M1</td>
<td>74</td>
<td>105</td>
<td>149</td>
<td>123</td>
<td>97</td>
<td>70</td>
<td>71</td>
<td>70</td>
</tr>
<tr>
<td>M2</td>
<td>128</td>
<td>91</td>
<td>118</td>
<td>94</td>
<td>77</td>
<td>45</td>
<td>58</td>
<td>80</td>
</tr>
<tr>
<td>M3</td>
<td>127</td>
<td>117</td>
<td>142</td>
<td>84</td>
<td>78</td>
<td>56</td>
<td>62</td>
<td>53</td>
</tr>
</tbody>
</table>
Dynamics – M1

High WMC Players

Low WMC Players
Dynamics – M2

High WMC Players

Low WMC Players
Dynamics – M3

High WMC Players

Low WMC Players
Dynamics – M1, GP
Dynamics – M2, GP
Dynamics – M3, GP
BDG

• Recall the seen digits in a backward order

Answer: 4.3.2.1
• Answer the final outcome in the box probed by “?”

Remember the digits

Do the arithematic operation

Answer: 8

Answer: 9

Answer: 3

Answer: 8
OS

- Recall the consonants in the correct order
- Distracter task: equation verification

Answer: H Z T

+ 2+8=5

H 5+6=10

Z 3+4=7

T ?
SS

• Recall the consonants in the correct order
• Distracter task: sentence verification

Answer: R T G
SSTM

- Reconstruct the dot pattern seen in the training phase
- Two to six dots

Draw the dot pattern using mouse