Cognitive Load and Strategic Sophistication

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Abstract

We study the relationship between the cognitive load manipulation and strategic sophistication. The cognitive load manipulation is designed to reduce the subject's cognitive resources which are available for deliberation on a choice. In our experiment, subjects are placed under a large cognitive load (given a difficult number to remember) or a low cognitive load (given a number which is not difficult to remember). Subsequently, the subjects play a one-shot game then they are asked to recall the number. This procedure is repeated for various games, where a new number is given for each game. We find a nuanced and nonmonotonic relationship between cognitive load and strategic sophistication. This relationship is consistent with two effects. First, subjects under a high cognitive load tend to exhibit behavior consistent with the reduced ability to compute the optimal decision. Second, the cognitive load tends to affect the subject's perception of their relative standing in the distribution of cognitive ability. The net result of these two effects depends on the strategic setting. Our experiment provides indirect evidence on the literature which examines the relationship between measures of cognitive ability and strategic sophistication.

Preliminary and incomplete
Comments welcome

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1 Introduction

Models of strategic sophistication have greatly improved our understanding of play in games.[1] These models posit that subjects exhibit heterogenous sophistication in their thinking of the game. An open question relates to the origin of these strategic levels and whether they arise from a fundamental trait of the subjects. A natural candidate for the source of the strategic levels is the measured cognitive ability of the subject. This has prompted researchers to investigate the relationship between measured cognitive ability and strategic sophistication.[2]

However, one difficulty in employing measures of cognitive ability is that subjects with different measures of cognitive ability are possibly also different in other ways. As such, it might not be possible to distinguish between an alternate hypothesis that an unobserved characteristic is responsible for the level of strategic sophistication, and cognitive ability is merely correlated with this characteristic. Here, rather than measure cognitive ability, we manipulate the cognitive resources available to the subject via cognitive load. Cognitive load experiments often direct subjects to make a decision in one domain while simultaneously manipulating the cognitive resources available to reflect on the decision.

The cognitive load manipulation is designed to occupy a portion of the working memory capacity of the subject. Working memory can be conceptualized as the cognitive resources available to temporarily store information so that it can be used in decision making. Therefore, working memory is instrumental in the execution of deliberative thought.[3] Several studies have found that measures of cognitive ability are positively related to measures of working memory capacity.[4] Further, reducing the available working memory of a subject via cognitive load, reduces the cognitive resources available for deliberation, and can be regarded as similar to the condition of having a lower cognitive ability. Additionally, given the within-subject

[1]For instance, Stahl and Wilson (1994,1995), Nagel (1995), Costa-Gomes, Crawford, and Broseta (2001), Costa-Gomes and Crawford (2006), Camerer, Ho, and Chong (2004). See Crawford, Costa-Gomes, and Iriberri (2013) for an updated overview of the field.

[2]See Bayer and Renou (2012), Burnham et al. (2009), Brañas-Garza, Paz Espinosa, and Rey-Biel (2011), Carpenter, Graham, and Wolf (2013), Devetag and Warglien (2003), Georganas, Healy, and Weber (2010), and Gill and Prowse (2012).

[3]See Alloway and Alloway (2013).

[4]For instance, see Conway, Kane, and Engle (2003), Kane, Hambrick, and Conway (2005), Oberauer et al. (2005), and Süß et al. (2002). See Burgess et al. (2011) and Cole et al. (2012) for recent advances in understanding the neurological basis of this relationship.

design of our experiment, we are able to observe the behavior of each of the subjects in different cognitive load treatments. As a consequence, our results are not possibly driven by unobserved characteristics which are only related to cognitive ability.[5]

Although we expected that the successful cognitive load manipulation would produce uniformly less strategically sophisticated behavior, we find a nuanced and nonmonotonic relationship between cognitive load and strategic sophistication. In fact, our results are consistent with recent advances in the literature. While much of the research on the source of strategic sophistication focuses on measures of cognitive ability, recent research emphasizes the role of the perception of the strategic sophistication of the opponent. For instance, Agranov et al. (2012) find that the strategic sophistication of the subject is related to the perceived strategic sophistication of their opponents.[6]

In our experiment, we direct subjects to play various one-shot games while under a cognitive load manipulation. In particular, we direct subjects to play ten 3×3 games, a variation of the $11-20$ game (Arad and Rubenstein, 2012), and a variation of the beauty contest game (Nagel, 1995). We note that our version of the $11-20$ game is relatively simple, the beauty contest is relatively complicated, and the 3×3 games have various levels of complexity.

The subjects play these games under either a low or a high cognitive load. Subjects in the low load are directed to commit a three digit binary number to memory and subjects under a high load are directed to commit a nine digit binary number to memory. Subsequently, the subjects are asked to recall the number.

Through a single manipulation of the available cognitive resources, we observe behavior consistent with two effects. First, subjects under a high cognitive load have difficulty making the computations associated with optimal play. In this regard, high load subjects can be considered to be less sophisticated than low load subjects. Second, subjects under a high load are aware that they were relatively disadvantaged in the cognitive ability distribution of the subjects. Therefore, high load subjects can be considered to be more sophisticated than low load subjects. We find that the net result of these two effects depends on the strategic

[5]Although we note that the research finds that the cognitive load manipulation is more effective on subjects with a higher measure of cognitive ability (Carpenter et al., 2013).

[6]Also see Alaoui and Penta (2012), Palacios-Huerta and Volij (2009), and Slonim (2005).

setting.

The effect of the constrained ability to make calculations dominates the other effect when, in the relatively complicated beauty contest game, the high load subjects select less strategic actions. This is consistent with the diminished ability of the high load subjects to compute the optimal strategy in the complicated game. Additionally, we see this effect dominating in that high load subjects have greater difficulty in predicting the actions of their opponents and they are more likely to behave as the relatively unsophisticated $L1$ type. Finally, we see this in that the subjects in the 3×3 games are less sensitive to the complexity of the game, as measured by the number of their own dominated strategies.

On the other hand, the effect of the reduction in their perceived standing in the cognitive ability distribution dominates the other effect in our version of the $11 - 20$ game, which is relatively uncomplicated. Here, high load subjects select a more strategic response, consistent with the expectation that they are paired with a more cognitively able subject. We also see this effect in that high load subjects are more likely to express beliefs which are consistent with their opponents playing their Nash Equilibrium strategy. Finally, we see this in that the subjects in the 3×3 games are more sensitive to the complexity of the game, as measured by the number of the dominated strategies of their opponent.

In summary, we find a nuanced and nonmonotonic relationship between available cognitive resources and strategic sophistication. We hope that our results are helpful in the efforts to improve the models of strategic sophistication.

1.1 Related literature

The economics literature increasingly regards the brain as an object worthy of study in that, subject to its limitations and heterogeneity across subjects, it is the generator of economic behavior. This line of inquiry has investigated topics ranging from the effects of sleep on strategic behavior (Dickinson and McElroy, 2010, 2012), to optimal search patterns (Sanjurjo, 2012a, 2012b), to neurological studies of the brain during choice (Coricelli and Nagel, 2009), to novel elicitation methods designed to measure the reasoning of subjects (Agranov, Caplin, and Tergiman, 2013; Burchardi and Penczynski, 2011; Chen et al., 2010; Crawford, 2008). In particular, there is a growing literature which investigates the relationship between measured cognitive ability and economic preferences[7] and the relationship between measured cognitive ability and behavior in games.[8] To the extent that subjects under a high cognitive load are similar to the condition of having a low cognitive ability, our results provide indirect evidence on the relationship between cognitive ability and strategic sophistication.

There is an extensive literature on the cognitive load manipulation in nonstrategic settings. The research finds that subjects under a high cognitive load are more impulsive and less analytical (Hinson, Jameson, and Whitney, 2003), they are more risk averse and are more impatient (Benjamin, Brown, and Shapiro, 2012), they make more mistakes on a forecasting task (Rydval, 2011), they exhibit less self control (Shiv and Fedorikhin, 1999; Ward and Mann, 2000, Mann and Ward, 2007), they fail to process available information (Gilbert, Pelham, and Krull, 1988; Swann et al., 1990), they perform worse on gambling tasks (Hinson, Jameson, and Whitney, 2002), they make different choices in allocation decisions (Cornelissen, Dewitte, and Warlop, 2011; Hauge et al., 2009, Schulz et al., 2012), and they have different evaluations of the fairness of outcomes (van den Bos et al., 2006). This literature finds that the behavior under a cognitive load is consistent with the condition that the subjects have fewer cognitive resources available for deliberative thought.

On the other hand, there does not exist many instances of studies of the strategic behavior which employ the cognitive load manipulation. To our knowledge, Roch et al. (2000), Cappelletti, Güth, and Ploner (2011), Duffy and Smith (2013), and Carpenter, Graham, and Wolf (2013) are the only such examples. We note that the first three of these papers are not designed to investigate models of strategic sophistication. For instance, Duffy and Smith (2013) direct subjects to play a finitely repeated multi-player prisoner's dilemma game while

[7]See Arruñada, Casari, and Pancotto (2012), Benjamin et al. (2012), Ben-Ner, Kong, and Putterman (2004), Brañas-Garza, Guillen, and Lopez del Paso (2008), Branstätter and Güth (2002), Burks et al. (2009), Chen et al. (2013), Cokely and Kelley (2009), Dohmen et al. (2010), Frederick (2005), Millet and Dewitte (2007), and Oechssler, Roider, and Schmitz (2009).

[8]See Ballinger et al. (2011), Baghestanian and Frey (2012), Bayer and Renou (2012), Brañas-Garza, Garcia-Muñoz, and Hernan Gonzalez (2012), Brañas-Garza et al. (2011), Carpenter et al. (2013), Chen et al. (2010), Gill and Prowse (2012), Jones (2011), Jones (2008), Palacios-Huerta (2003), Putterman, Tyran, and Kamei (2011), Rydval (2011), Rydval and Ortmann (2004), and Schnusenberg and Gallo (2011).

under a differential cognitive load. The authors find that the low load subjects exhibit more defection near the end of play and they are better able to condition their strategy on previous outcomes. However, their study does not immediately lend itself to the study of strategic sophistication, as the games are repeated and the subjects receive feedback about the strategic outcomes.

In contrast to these three studies, Carpenter et al. (2013) induce a differential cognitive load in subjects then observe the strategic sophistication of the subjects. The subjects play a sequential game which can be solved by backwards induction. The subjects also provide both actions and beliefs in the beauty contest game. The authors find that subjects under a high cognitive load are less strategic in that they are less able to perform backwards induction. Additionally, the authors find that high load subjects believe that their beauty contest opponents select a higher number and the authors observe a larger deviation from the best response to these beliefs. Our most comparable result is that we find that high load subjects are less strategic in that they select a higher number in the beauty contest. While our beauty contest results coincide with those of Carpenter et al., we also note that we find instances where the high load subjects can be considered to be more strategic.

We also note that there are methodological differences between Carpenter et al. and our paper. First, Carpenter et al. employs a between-subjects design, whereby subjects are exclusively observed in a single cognitive load treatment. This design introduces possible differences in payments across treatments, since correctly performing the memorization task pays an additional amount. By contrast, we employ a within-subjects design, whereby each subject plays some games under a high load and other games under a low load. Therefore, the differences which we observe are not possibly driven by differences in the payments across the cognitive load treatments.

In our view, this paper makes two contributions to the literature. First, we provide additional evidence that the cognitive load manipulation affects strategic behavior. Second, we find that the relationship between strategic sophistication and available cognitive resources is nuanced and nonmonotonic. In fact, this nuanced relationship is achieved through only a single cognitive load manipulation. We view our results as providing indirect evidence which could inform the research on the relationship between measures of cognitive ability and strategic sophistication. In particular, our results suggest that a lower measure of cognitive ability will not necessarily produce less sophisticated behavior, particularly when the ability to make the necessary computations is not a binding constraint.

2 Method

A total of 164 subjects participated in the experiment. The subjects were drawn from the experimental economics subject pool at Rutgers University-New Brunswick and the sessions were conducted in the Wachtler Experimental Economics Laboratory. The experiment was programmed and conducted with the software z-Tree (Fischbacher, 2007).[9] There were 5 sessions of 20 subjects and 4 sessions of 16 subjects. Sessions lasted from 60 to 75 minutes.

2.1 Specification of the games

We direct subjects to play a series of games: ten 3×3 games, an adaptation of the $11 - 20$ game, and an adaptation of the beauty contest game. These games are used because they provide different estimates of the strategic sophistication of the subjects. The subjects are not given feedback about the outcomes of the games. The subjects are told that they would be randomly and anonymously rematched in each of the games.

First, we direct subjects to play 10 simultaneous action 3×3 games. These games are simplified versions of games used by Costa-Gomes and Weizsacker (2008), Rey-Biel (2008), and Bayer and Renou (2012).[10] In these games, each subject is matched with another subject and both make a selection among three possible actions. In addition to selecting an action, we also elicit the point beliefs of the subjects about the action of the other player. Each of the 3×3 games has an original version (labeled A) and a transposed version of the original game (labeled B). In other words, the A and B versions are strategically equivalent but the roles have been switched. From the perspective of the games as specified in the appendix,

[9] The z-Tree code is available from the corresponding author upon request.

[10] See the appendix for the precise specification of the games used and a screen shot.

subjects play all 10 games as either a row or a column player. Therefore, each subject plays both roles in each of the 5 strategically equivalent games. We note that the game is always presented so that the subject is the row player and the opponent is the column player. As a result, every player selects among actions labeled Top, Middle, and Bottom, and selects beliefs about the action of the opponent which are labeled Left, Center, and Right. Throughout the experiment, 10 points are equivalent to \$3.50. Correct beliefs are rewarded with 4 points. See the appendix for a screenshot of the choice in the 3×3 games.

We also use a variant of the $11 - 20$ game (Arad and Rubenstein, 2012). Subjects are randomly matched with another subject and select an integer between 1 and 10. The subjects receive the amount selected, where again 10 points were equivalent to \$3.50. However, the subject receives a bonus of 10 points if they select a number exactly one digit lower than their opponent. Hereafter, we will refer to this game as the *1 − 10* game.

Finally, we employ a version of the beauty contest game (Nagel, 1995). Each subject selects a half-integer between 0 and 10. The subject who selects the number closest to 2/3 of the average in the session receives \$30.

2.2 Memorization task

Before play in every game, the subjects are given up to 15 seconds to commit a number to memory. The subjects are told that the number is to be retained during the play of the game, and after the game, the subject would be asked for the number. These numbers are always composed of a string of either 0 or 1, where the first digit is always a 1. In the high load treatment, we require the memorization of a 9 digit string, for example: 101110001. In the low load treatment, we require the memorization of a 3 digit string, for example: 110. We employ a within-subject design whereby the subjects face an alternating load of high and low. Half of the subjects are given the high load first, and half are given the low load first. A new number is randomly given in each of the games. The subjects are not given feedback about the results of the memorization task.

2.3 Experimental timeline and details

Before the incentivized portion of the experiment, we provide four unincentivized tasks: two practice memorization tasks and two simple addition tasks. First, the subjects are given two unincentivized practice rounds with the memorization task, one with a large number and one with a small number. Then, in order to illustrate the extent to which the loads can affect the ability to make basic computations, we provide a memorization number, then we direct the subjects to sum two randomly selected integers between 11 and 40, then we ask for the memorization number. The subjects perform this addition task under both a low and a high cognitive load.

Subsequently, we provide the subjects with instructions on 3×3 games.[11] We direct the subjects to play the 3×3 games under a differential cognitive load. Before each of these games, we give the subjects the memorization number, then we present the game, then we ask for the memorization number. The instructions state that, should the subject perform X of the 10 memorization tasks correctly in the 3×3 games then the computer would randomly select the maximum of either 0 or $X - 7$ outcomes of the 3×3 games for payment.

Between each of the ten 3×3 games, the subjects are forced to take a 20 second rest. During this rest period, the subjects are not able affect the screen which reads, "Rest!!! Because a new game will start soon." Also note that, across sessions, we randomize the order in which the subjects are presented the 3×3 games.

After the 3×3 games, the subjects are directed to play the $1 - 10$ game and the beauty contest game, under the alternating cognitive load which continues from the previous stages. The subjects are told that they would be paid the amount of the $1 - 10$ game and the beauty contest game only if the memorization task is performed correctly for both of these games. Note that we do not load the subjects when they are reading the instructions for the $1 - 10$ game and the beauty contest game.

After the beauty contest memorization task is completed, the subjects are directed to indicate their gender, whether they are an economics major, whether they have taken a game

[11] These instructions are available from the corresponding author upon request.

theory course, an optional estimate of their grade point average (GPA), and a rating of the difficulty in recalling the large and the small memorization numbers. These difficulty ratings are solicited on a scale of 1 ("Very Difficult") to 7 ("Not Very Difficult"). Subsequently, the subjects are told their amount earned and they are paid in cash. The subjects earned an average of $17.89.

2.4 Discussion of the experimental design

We now discuss our experimental design. First, despite that Duffy and Smith (2013) find that their cognitive load manipulation affects behavior, here we employ a different design. First, we employ a within-subject design, rather than a between-subject design. This is notable because research suggests that the effects of the cognitive load manipulation can be lasting (Dewitte et al., 2005). In order to mitigate the effects of the load of previous rounds, we employ a mandatory rest-period between games. Second, unlike Duffy and Smith (2013), which employs a memorization number composed of digits ranging from 0 to 9, we restrict attention to numbers composed exclusively of either 0 or 1. This design avoids the possibility that the memorization task interacts with the payoff numbers in the games.

While we could observe that subjects were not able to employ any obvious memorization aids (cell phones, writing the number on paper, etc.) we cannot say with certainty that no subject used a memorization aid. For instance, with an appropriate positioning of the free body parts (feet, legs, elbows, wrists, and fingers on left hand) one could possibly devise a code to aid memorization. In our view, this possibility is not as advantageous as it first appears. This is because the subject must remember the code, and this will occupy cognitive resources. So, while this remains a possibility, we do not regard it to be a serious problem.

Additionally, we design the experiment so that the responses to the games are as simple as possible. For instance, in the 3×3 games we elicit the point beliefs of the action of the opponent rather than more sophisticated measures of beliefs. This procedure can have a drawback in that our measures of beliefs are somewhat coarse. On the other hand, the task is sufficiently simple so that the memorization task is not likely to affect the ability to comply with the elicitation procedure. Additionally, we elicit responses to the beauty contest, which are the 21 half-integers between 0 and 10 rather than, as is more standard, the integers or real numbers between 0 and 100. More generally, we design the experiment so that every response in the games takes a different format than that required for the memorization task. In the 3×3 games, the $1-10$ game, and the beauty contest game, the responses involve clicking on the corresponding button, whereas the memorization task requires entering a sequence of digits.

We employ a simplified version of the 3×3 games originally used by Costa-Gomes and Weizsacker (2008), Rey-Biel (2008), and Bayer and Renou (2012). The original games have integer payoffs which range from 10 to 98. We employ a simplified version where payoffs are integers which range from 1 to 11. This would seem to reduce the computational difficulty in deciding on an action.

We now discuss the equilibrium details of the games. The 3×3 games each have a single pure strategy Nash Equilibrium. The $1-10$ game does not have a pure strategy equilibrium, but has a unique mixed strategy equilibrium. In equilibrium, the player selects 10 with probability 0.1, 9 with probability 0.2, 8 with probability 0.3, and 7 with probability 0.4. The beauty contest game has a unique Nash Equilibrium where every player selects 0. Although the $1-10$ game has a mixed strategy equilibrium, the beauty contest is a more complicated game. First, there are several opponents in the beauty contest game, whereas there is only a single opponent in the $1-10$ game. Second, the best response in the $1-10$ game is obvious: select one fewer than your opponent. This is in contrast to the beauty contest where the best response is less straightforward. Finally, there are many decision rules in the beauty contest: the pure strategy Nash Equilibrium or successive elimination of dominated strategies. By contrast, in the $1-10$ game there is only a single decision rule: select one fewer than your opponent. This is because the game possesses neither a pure strategy Nash Equilibrium nor a dominated strategy.

Finally, we note that we do not load the subjects during the instructions of the $1-10$ game and the beauty contest game because this could reduce the comprehension of the instructions.[12]

[12] We acknowledge that this design leaves open the possibility that the subject could decide on an action

3 Results

3.1 A preliminary look at the cognitive load effects

The subjects report a significant difference in the difficulty in recalling the large number ($M = 5.86$, $SD = 1.28$) and the small number ($M = 6.83$, $SD = 0.57$) according to a Wilcoxon signed-rank test, $W = 2142$, $p < 0.001$. There are also significant differences between the treatments in the length of time which they spend committing the number to memory. Recall that the subjects are given up to 15 seconds in order to commit the number to memory. The low load subjects have significantly more of the 15 seconds remaining ($M = 12.58$, $SD = 3.08$) than the high load subjects ($M = 4.71$, $SD = 4.30$), according to a Wilcoxon-Mann-Whitney rank-sum test $Z = 33.55$, $p < 0.001$. The subjects are each given 12 incentivized memorization tasks, 6 as high load and 6 as low load. Subjects in the low load are correct in 98.88% (972 of 984) of the attempts and the subjects in the high load are correct in 97.05% (955 of 984) of the attempts.[13]

Despite these differences between the treatments, we do not find evidence that the subjects in the high load treatment are unusually impaired. Recall that we pose 2 simple, unincentivized arithmetic questions to each subject, one under a high load and one under a low load. Given 328 arithmetic questions, only 10 incorrect responses are given, 6 under the high load and 4 under the low load. Thus, we do not find evidence that the high load significantly impairs the subjects.

3.2 The $1 - 10$ game

Recall that the $1 - 10$ game is relatively simple and provides a straightforward measure of strategic sophistication. It would seem natural that the least sophisticated subject ($L0$) would select 10. The subject who best responds to the $L0$ subjects ($L1$) would select 9. The subject who best responds to $L1$ subjects ($L2$) would select 8, and so on. As such, the response is negatively associated with the strategic sophistication of the subject.

during the instruction stage, thereby reducing the efficacy of the cognitive load.

[13] According to a Wilcoxon-Mann-Whitney rank-sum test, these are significantly different, $Z = 2.87$, $p = 0.004$.

As the response in the $1-10$ game is bounded above at 10 and below at 1, we perform tobit regressions with the $1-10$ game choice as the dependent variable, subject to these bounds. We include a dummy variable indicating whether the $1-10$ game is played under a high load. This variable obtains a value of 1 if the subject is under a high load and a 0 otherwise. In addition to the high load dummy, we also include a dummy variable indicating whether the subject has taken a game theory class, whether the subject reports being an economics major, whether the subject is female, and their self-reported GPA. Recall that GPA is optional and only 112 of 164 subjects provide a response. We summarize this analysis in Table 1 below.

Table 1 Tobit regressions with choice in the $1-10$ game

	(1)	(2)	(3)
High load	-0.613^{**}	-0.631^{**}	-0.526^{*}
	(0.286)	(0.286)	(0.308)
Economics major	–	-0.499	-0.667
		(0.389)	(0.444)
Game theory	–	-0.836	-0.727
		(0.628)	(0.704)
Female	–	-0.278	0.143
		(0.291)	(0.311)
Self-reported GPA	–	–	0.210
			(0.391)
Observations	164	164	112
-2 Log Likelihood	603.08	597.84	383.06

The tobit regressions are performed with an upper bound of 10 and a lower bound of 1. Note that * indicates significance at $p < 0.1$ and ** indicates significance at $p < 0.05$.

Our analysis finds evidence that the subjects under a high load give a significantly lower response in the $1-10$ game. To the extent that smaller responses are associated with a greater strategic sophistication, this provides evidence that high load subjects are more strategic in the $1-10$ game than low load subjects.

3.3 The beauty contest game

We note that lower responses in the beauty contest are associated with greater strategic sophistication. Recall that choice in the beauty contest is bounded above by 10 and below by 0. Therefore, we run tobit regressions with choice in the beauty contest as the dependent variable, subject to these bounds. The analysis is otherwise equivalent to that summarized in Table 1. We summarize this analysis in Table 2.

Table 2 Tobit regressions with choice in the beauty contest game

	(1)	(2)	(3)
High load	0.677*	0.647	0.941**
	(0.394)	(0.397)	(0.434)
Economics major	–	−0.138	−0.379
		(0.549)	(0.634)
Game theory	–	−0.189	0.460
		(0.888)	(1.007)
Female	–	0.634	0.397
		(0.404)	(0.438)
Self-reported GPA	–	–	−2.079***
			(0.550)
Observations	164	164	112
-2 Log Likelihood	742.82	739.78	489.32

The tobit regressions are performed with an upper bound of 10 and a lower bound of 0. Note that * indicates significance at $p < 0.1$, ** indicates significance at $p < 0.05$, and *** indicates significance at $p < 0.01$.

The high load dummy is positive and significant at 0.1 in regression (1), and at 0.05 in regression (3). This suggests that subjects under the high load are less strategic than subjects under a low load. We also note that the self-reported GPA is negatively related to choice in the beauty contest. This suggests that higher GPA subjects act more strategically in the beauty contest.

Thus far, we find that high load subjects are more strategic in the $1 - 10$ game and less strategic in the beauty contest. This behavior is consistent with two effects of the cognitive load. First, the computational ability of high load subjects is constrained. Second, the high load subjects are aware that their computational ability is constrained, and they regard their opponent as more sophisticated. These effects have different implications in a relatively uncomplicated game ($1-10$ game) and a relatively complicated game (beauty contest game).[14]

[14] In support of our contention that the beauty contest is more complicated than the $1 - 10$ game, we note that GPA is related to choice in the beauty contest but not in the $1 - 10$ game.

In the uncomplicated game, where computational ability is not a binding constraint, the second effect dominates. In a complicated game, where computational ability is possibly a binding constraint, the first effect dominates.

We note that there is an alternate explanation for our results involving the $1-10$ game and the beauty contest game. Recall that the load alternates across these games. For instance, low (high) load subjects in the $1-10$ game are high (low) load subjects in the beauty contest game. It is possible that these results are due to unchanging, subject-specific traits, rather than the result of the load. However, we note that there is not a significant relationship between any of the observable variables and the load treatment in these two games.[15]

3.4 The 3×3 games

We first examine the relationship between cognitive load and a measure of the sophistication of the beliefs of the subjects. One measure of the sophistication of the beliefs of the subject is whether the subjects reports beliefs which are consistent with the Nash Equilibrium action of the opponent. In the analysis which follows, the dependent variable, Nash beliefs, obtains a value of 1 if the subjects states beliefs which are consistent with the Nash Equilibrium action, and a 0 otherwise.

Since the 3×3 games vary in their complexity, we include this feature in the analysis. We include an independent variable which lists the number of the subject's own dominated strategies. This variable ranges from 0 to 2. We also include an independent variable which lists the number of dominated strategies of the opponent. This variable also ranges from 0 to 2. As in the previous analysis, we account for the load by employing the high load dummy variable. Additionally, we include a dummy variable indicating whether the subject has taken a game theory course, whether the subject reports being an economics major, and whether the subject is female. In the analysis below, we refer to this collection of variables as *Demographics*. Finally, we account for self-reported GPA.

Since we have 10 observations from each subject, we employ a repeated measures analysis. We estimate an unstructured covariance matrix, clustered by subject. In other words,

[15] These results are available from the corresponding author upon request.

we assume a unique correlation between any two observations involving a particular subject. However, we assume that observations involving two different subjects are statistically independent. Moreover, since the subjects each play 10 games, and there are two players per game, there are 20 different roles: 10 for *row* players and 10 for *column* players. Therefore, we estimate two such covariance matrices, one for row players and one for column players. The regressions are estimated using maximum likelihood. We summarize this analysis in Table 3.

Table 3 Repeated measures regressions of Nash beliefs

	(1)	(2)	(3)
High load	0.0807**	0.0777**	0.0439
	(0.0365)	(0.0367)	(0.0420)
Own dominated strategies	0.0652***	0.0646***	0.0258
	(0.0149)	(0.0149)	(0.0167)
Other dominated strategies	0.239***	0.239***	0.272***
	(0.0152)	(0.0151)	(0.0176)
High load-Own DS interaction	−0.0542**	−0.0526**	−0.0381
	(0.0213)	(0.0213)	(0.0231)
High load-Other DS interaction	0.0226	0.0232	0.0217
	(0.0205)	(0.0204)	(0.0235)
GPA	–	–	0.0829***
			(0.0307)
Demographics	*No*	*Yes*	*Yes*
Observations	1640	1640	1120
-2 Log Likelihood	1714.1	1720.8	1120.1
χ^2 Likelihood Ratio	365.50***	366.44***	328.07***

The repeated measures regressions estimate an unstructured covariance matrix for row players and an unstructured covariance matrix for column players, clustered by subject. We do not provide the estimates of the intercept, the individual demographics variables, or the covariance matrices. Regressions (1) and (2) have 1640 observations (164 subjects in 10 periods) and regression (3) has 1120 observations (112 subjects in 10 periods). Finally, * denotes significance at $p < 0.1$, ** at $p < 0.05$, and *** at $p < 0.01$.

Regressions (1) and (2) show evidence of a positive relationship between cognitive load and strategic sophistication, as measured by Nash beliefs. This suggests that high load subjects express beliefs that their opponents are more sophisticated than do the low load subjects. Although this is not robust to the specification which accounts for the self-reported GPA, we note we found a similar effect in the $1-10$ game. There we found that high load subjects behave in a way which is consistent with more sophisticated beliefs.

We also note that the beliefs of high load subjects are less sensitive to the specification of the game. However, we note that this is not robust to the specification involving the self-reported GPA.

Next we explore the relationship between cognitive load and a commonly used measure of strategic sophistication. In the strategic sophistication literature, $L1$ subjects are defined to be those best responding to opponents who are the least sophisticated ($L0$) types. Typically in matrix games, the $L0$ types are assumed to select each available action with an equal probability. In our setting, this would imply that the opponent selects each action with probability $\frac{1}{3}$. Needless to say, $L1$ subjects exhibit a relatively low level of strategic sophistication. In the analysis below, the dependent variable, $L1$ classification, obtains a value of 1 if the subject selects an action consistent with $L1$ behavior and a 0 otherwise. The analysis closely follows that summarized in Table 3, with the exception that we include two additional independent variables. We include an interaction between the number of the own dominated strategies and number of the dominated strategies of the opponent. We also include the interaction between this interaction variable and the high load dummy. This analysis is summarized in Table 4.

Table 4 Repeated measures regressions of $L1$ classification

	(1)	(2)	(3)
High load	0.142^{***}	0.142^{***}	0.136^{**}
	(0.0464)	(0.0465)	(0.0538)
Own dominated strategies	0.146^{***}	0.146^{***}	0.174^{***}
	(0.0223)	(0.0223)	(0.0263)
Other dominated strategies	-0.0280	-0.0286	-0.0388
	(0.0262)	(0.0262)	(0.0311)
High load-Own DS interaction	-0.0851^{**}	-0.0859^{**}	-0.108^{***}
	(0.0349)	(0.0349)	(0.0401)
High load-Other DS interaction	-0.107^{***}	-0.106^{***}	-0.0842^{*}
	(0.0386)	(0.0388)	(0.0454)
GPA	–	–	0.128^{***}
			(0.0425)
Demographics	*No*	*Yes*	*Yes*
Observations	1640	1640	1120
-2 Log Likelihood	1903.0	1914.4	1253.3
χ^2 Likelihood Ratio	321.22^{***}	319.06^{***}	268.03^{***}

The repeated measures regressions estimate an unstructured covariance matrix for row players and an unstructured covariance matrix for column players, clustered by subject. We do not provide the estimates of the intercept, the individual demographics variables, the covariance matrices, the interaction between the number of own and the number of other dominated strategies, and the interaction with this variable and the high load dummy. Regressions (1) and (2) have 1640 observations (164 subjects in 10 periods) and regression (3) has 1120 observations (112 subjects in 10 periods). Finally, * denotes significance at $p < 0.1$, ** at $p < 0.05$, and *** at $p < 0.01$.

We first note that the subjects under a high load are more likely than low load subjects to be classified as $L1$. This suggests that subjects under a high load exhibit less strategic sophistication than subjects under a low load. We also note that the two interaction terms are significant and negative. In particular, this suggests that the strategic sophistication of high load subjects is less sensitive to the number of their own dominated strategies. Additionally, the strategic sophistication of high load subjects is more sensitive to the number of the dominated strategies of their opponent.

Finally, we note that the GPA coefficient is significant and positive. This suggests that higher GPA people are more likely to behave as an $L1$ type. Perhaps we find this result because the $L1$ classification has an adjacent, less sophisticated classification ($L0$) and an adjacent, more sophisticated classification ($L2$). Therefore, whereas we consider the $L1$ classification to be relatively unsophisticated, perhaps low GPA subjects are not sufficiently sophisticated to even be considered $L1$.

We now investigate the relationship between the accuracy of the stated beliefs and the cognitive load. In particular, we now compare the stated beliefs with the distribution of actions in the game. Note that 82 players are given the role of column players and 82 are given the role of row players. We calculate the distribution of play of both of these treatments for each game. Within the 82 players in each role, 48 make their decision under one cognitive load treatment and 34 make their decision under the other. The calculation of the distribution of the play accounts for this imbalance by equally weighting both cognitive load treatments. In this analysis, the dependent variable takes a value of 1 if the subject indicates beliefs identical to the most common action played by the 82 subjects in the opposite role for that particular game. The analysis is otherwise equivalent to that summarized in Table 4. We summarize this analysis in Table 5.

Table 5 Repeated measures regressions of correct beliefs of distribution of actions

	(1)	(2)	(3)
High load	-0.109^{**}	-0.109^{**}	-0.104^{**}
	(0.0440)	(0.0440)	(0.0486)
Own dominated strategies	-0.116^{***}	-0.117^{***}	-0.118^{***}
	(0.0269)	(0.0269)	(0.0284)
Other dominated strategies	0.112^{***}	0.112^{***}	0.135^{***}
	(0.0219)	(0.0219)	(0.0226)
High load-Own DS interaction	0.0501	0.0507	0.0659
	(0.0396)	(0.0395)	(0.0435)
High load-Other DS interaction	0.0851^{***}	0.0855^{***}	0.0855^{***}
	(0.0307)	(0.0306)	(0.0307)
GPA	–	–	0.104^{***}
			(0.0302)
Demographics	No	Yes	Yes
Observations	1640	1640	1120
-2 Log Likelihood	1798.9	1803.3	1144.8
χ^2 Likelihood Ratio	346.94^{***}	349.84^{***}	329.70^{***}

The repeated measures regressions estimate an unstructured covariance matrix for row players and an unstructured covariance matrix for column players, clustered by subject. We do not provide the estimates of the intercept, the individual demographics variables, the covariance matrices, the interaction between the number of own and the number of other dominated strategies, and the interaction with this variable and the high load dummy. Regressions (1) and (2) have 1640 observations (164 subjects in 10 periods) and regression (3) has 1120 observations (112 subjects in 10 periods). Finally, * denotes significance at $p < 0.1$, ** at $p < 0.05$, and *** at $p < 0.01$.

First, we find evidence that subjects under a high load have less accurate beliefs than the low load subjects. Specifically, in each regression we find that the high load coefficient is negative and significant at 0.05. We also find that the interaction between the high load dummy and the number of other dominated strategies is positive and significant. This suggests that the accuracy of the beliefs of high load subjects is more sensitive than the beliefs of low load subjects to the number of dominated strategies of the other player.

4 Conclusion

We have described an experiment where subjects play a sequence of games designed to measure their strategic sophistication while under a differential cognitive load. These games include ten 3×3 games, the $1 - 10$ game, and the beauty contest game. Through our single cognitive load manipulation we observe a nuanced relationship between available cognitive resources and strategic sophistication. This behavior is consistent with two effects. First, subjects under a high cognitive load have difficulty in making the computations associated with optimal play. Second, subjects under a high load are aware that they are relatively disadvantaged in the cognitive ability distribution of the subjects. The net result of these effects depends on the strategic setting.

We see the first effect dominating the second effect when, in the relatively complicated beauty contest game, the high load subjects play less strategically. This behavior is consistent with the diminished ability of subjects to compute the optimal strategy in this complicated setting. We additionally see this effect dominating in that high load subjects have a greater difficulty in predicting the actions of their opponents and they are more likely to behave as the relatively unsophisticated $L1$ type. Finally, we see this in that the subjects in the 3×3

games are less sensitive to the complexity of the game, as measured by the number of their own dominated strategies.

On the other hand, we see the second effect dominating the first effect when, in the relatively uncomplicated $1-10$ game, the subjects select a more strategic response, expecting to be paired with a more cognitively able subject. We also see this effect in that high load subjects are more likely to express beliefs which are consistent with their opponents playing the Nash Equilibrium strategy. Finally, we see this effect dominating in that the subjects in the 3×3 games are more sensitive to the complexity of the game, as measured by the number of the dominated strategies of their opponent.

We hope that this research is helpful in suggesting improvements in existing models of strategic sophistication. Our evidence suggests that constraints on cognitive resources can affect the computations involving optimal behavior but also the perception of the subjects' relative standing in the distribution of cognitive resources. Our research corroborates previous research that these two effects are important in the study of games. In particular, our results suggest that a lower measure of cognitive ability will not necessarily produce less sophisticated behavior, particularly when the ability to make the necessary computations is not a binding constraint.

We also hope that this research will encourage the use of the cognitive load manipulation in any setting in which cognition plays a crucial role in behavior. Perhaps the most obvious application of cognitive load is in the rational inattention literature.[16] Rational inattention models assume that decision makers are unable to process all available information. However, decision makers optimally allocate their limited attention. It would seem profitable to investigate these models in the laboratory, by manipulating the limits of attention via cognitive load.

We acknowledge that there is much work to be done on this topic. For instance, we were not able to observe the order in which the subjects provided their action and their beliefs in the 3×3 games. In the future, it could be profitable to observe if there is a relationship

[16] See Sims (2003), Reis (2006), Mackowiak and Wiederholt (2009), Wiederholt (2010), Dahremöller and Fels (2012), and Persson (2012). See Cheremukhin, Popova, and Tutino (2012) for an experiment involving rational inattention.

between the cognitive load manipulation and the order of the selection of actions and beliefs. We also hope to learn whether there is a differential effect of not soliciting beliefs. Perhaps the solicitation of beliefs prompts the high load subjects to be aware of the strategic considerations, where that would possibly not occur if beliefs were not solicited. Finally, we are interested to learn the implications of a more difficult high load (more than 9 binary digits) and a less difficult low load (less than 3 binary digits).

Appendix

In the games below, 10 points are equivalent to \$3.50. Games 1A and Game 1B: both players have 2 dominated strategies. The game is adapted from Game 1 of Bayer and Renou (2012).

Game 1A

	Left	Center	Right
Top	8, 4	5, 7	3, 6
Middle	6, 8	4, 9	1, 2
Bottom	7, 1	2, 5	2, 4

Game 1B

	Left	Center	Right
Top	2, 8	3, 1	8, 7
Middle	6, 6	4, 3	9, 5
Bottom	5, 4	1, 1	7, 3

Games 2A and 2B: one player has a dominated strategy and the other player has two. The game is adapted from Game 3 of Bayer and Renou (2012).

Game 2A

	Left	Center	Right
Top	8, 8	3, 5	1, 9
Middle	9, 2	5, 3	6, 4
Bottom	4, 1	7, 6	2, 8

Game 2B

	Left	Center	Right
Top	4, 5	6, 3	7, 7
Middle	3, 9	9, 8	2, 4
Bottom	5, 6	10, 1	9, 2

Games 3A and 3B: one player has two dominated strategies, the other player does not have any dominated strategies. The game is adapted from Game VS1R of Rey-Biel (2008).

Game 3A

	Left	Center	Right
Top	1, 9	2, 6	4, 3
Middle	4, 4	5, 4	5, 4
Bottom	7, 3	7, 5	6, 8

Game 3B

	Left	Center	Right
Top	10, 2	2, 10	7, 11
Middle	7, 3	6, 4	7, 10
Bottom	6, 6	1, 7	9, 8

Games 4A and 4B: one player has one dominated strategy, other player does not have a dominated strategy. The game, adapted from Game VS2R of Rey-Biel (2008), is dominance solvable.

Game 4A

	Left	Center	Right
Top	6, 6	4, 8	4, 9
Middle	4, 8	11, 3	3, 5
Bottom	1, 10	10, 6	3, 8

Game 4B

	Left	Center	Right
Top	11, 1	1, 8	7, 5
Middle	4, 8	4, 8	1, 11
Bottom	6, 5	5, 7	2, 5

Games 5A and 5B: neither player has a dominated strategy. The game is adapted from Game VSNDR of Rey-Biel (2008).

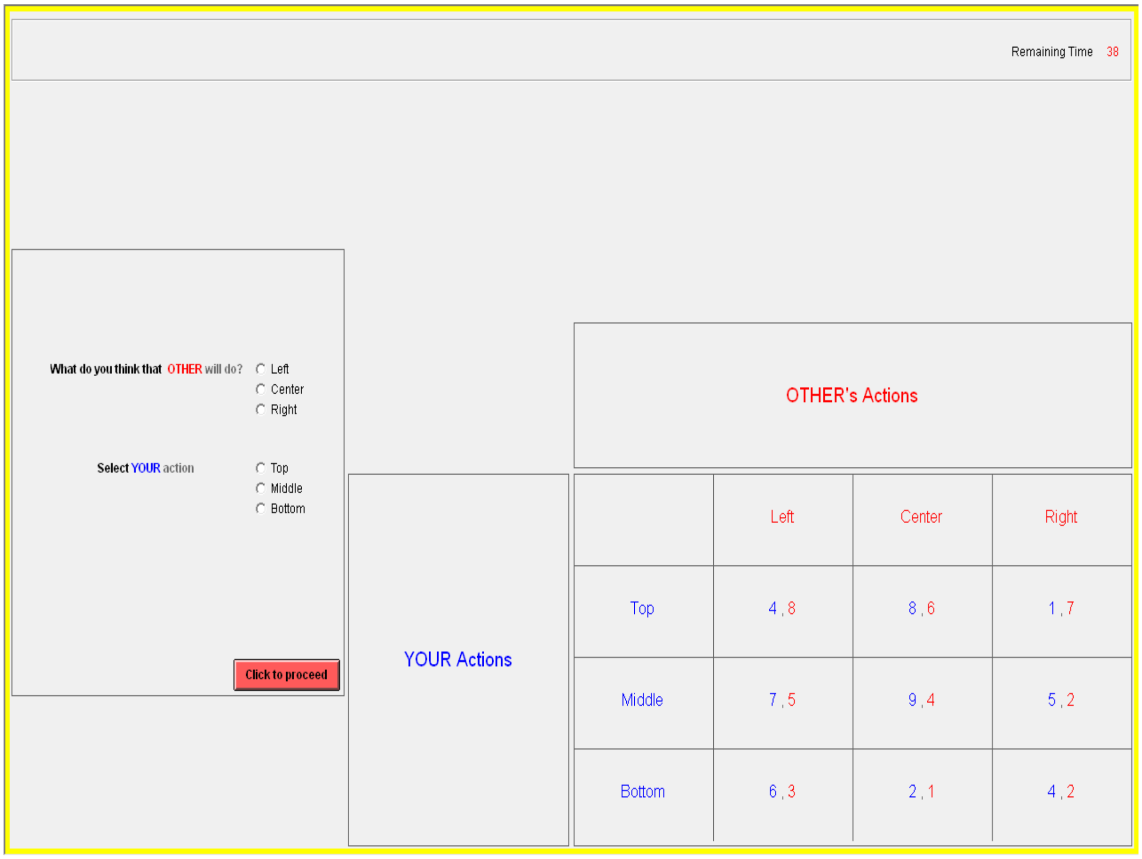
Game 5A

	Left	Center	Right
Top	8, 6	2, 6	1, 11
Middle	4, 6	7, 6	3, 6
Bottom	2, 7	2, 5	4, 4

Game 5B

	Left	Center	Right
Top	3, 10	5, 5	3, 9
Middle	4, 9	2, 9	4, 9
Bottom	9, 5	3, 8	2, 7

The screen during the game decision:



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