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Decision making under uncertainty: An experimental study in market settings

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Introduction

We present an empirical, experimental investigation of the most important theories of decision under uncertainty. The theories are important for two reasons. One is that they represent a normative expression of rationality: one can argue that people should be advised to behave as the theory recommends. The other reason is that economists and financial analysts assume routinely that agents behave according to these theories. It is important to understand to what degree do agents in reality behave as assumed.

Our main focus is on subjective expected utility theory (SEU). Imagine an agent (i.e., an individual) choosing a portfolio of financial assets. The theory postulates that the agent behaves as if she assigned subjective probabilities to each possible eventuality, and has a "utility" evaluating monetary payoffs: that is, the agent has a subjective evaluation of monetary quantities.[1] Then the agent chooses so as to maximize the expected value of her utility, where the expectation is calculated according to her subjective probabilities.

A set of normative criteria have been proposed (Savage, 1954) that imply that an agent must follow SEU theory. The criteria are "normative" in the sense that a rational agent should be advised to follow them. They include, for example, that an agent should not be exploited through a "money pump" scheme. One of the most famous and controversial criteria is the "sure thing principle," which roughly says that two uncertain payoffs should only be compared on the events where they differ. To sum up, there are strong arguments in favor of recommending that agents should behave according to SEU, and many economists would agree that from the normative viewpoint, SEU is the correct theory.

[1] The subjective evaluation of money may not change one-for-one with monetary quantities. For example, a rich person may subjectively value an additional dollar less than a poor person would.

Aside from normative considerations, economists and other analysts routinely assume that agents behave according to SEU. SEU is ubiquitous in the economic and finance literatures, and plays a central role in economic modeling—ranging from abstract models of general equilibrium to practical recommendations made by consulting companies and financial practitioners. In this sense, SEU is a "positive" theory that seeks to explain actual observed choices made in situations of uncertainty.

While SEU is the dominant theory of choice under uncertainty, it is well known to face empirical challenges. In an influential paper, Ellsberg (1961) suggested that many agents would not conform to SEU. The phenomenon he uncovered, known as the "Ellsberg paradox," suggests that agents may wish to avoid bets on uncertain events, in ways that cannot be represented with a single subjective probability. This avoidance is termed "ambiguity aversion."

The Ellsberg paradox is based on a thought experiment, using the choice of bets based on drawing balls from urns. One of our contributions is to empirically assess SEU in an economic setting that closely resembles the real-world environments (a financial market context in our study) where economists routinely assume that SEU guides agents' choices.

To account for the Ellsberg paradox, researchers have developed generalizations of SEU. Gilboa and Schmeidler (1989) suggest that an agent in Ellsberg's example may have too little information to form a unique subjective belief, and hence entertains multiple subjective probabilities. Being ambiguity averse, the agent maximizes the minimal (worst-case) expected utility over all subjective probabilities she entertains. The resulting theory is called maxmin expected utility (MEU). On the other hand, Machina and Schmeidler (1992) postulate that agents may have a unique subjective probability, but do not necessarily decide according to the expected utility with respect to this probability. Such agents are called probabilistically sophisticated.

The positive and normative arguments in favor of SEU have practical implications. For example, a pension fund may advise agents on how to choose a portfolio for their retirement accounts. Such recommendations are meant to capture agents' best interests, and seek to assess how they trade off volatility and returns. As a matter of fact, the recommendations should be based on a model of agents' preferences: otherwise it is not clear that they are in the agents' best interest. Economic models (SEU and MEU in our case) which better capture agents' (that is individual) preferences would lead to better recommendations to the agents in terms of their welfare.

To know what is best for a client, the fund would need a model that captures the client's welfare. Economists have long understood welfare (or "preference") to be revealed through choices: giving rise to the term "revealed preference." The models we evaluate in our study seek to capture agents' welfare, and their empirical validity can only be assessed through a study of agents' choices: through a study of revealed preference. Thus, our results provide an evaluation of some of the most commonly used models of agent welfare, models that underlie normative welfare evaluations and practical financial advice.

Experiments

Ambiguity aversion has been identified in many different contexts and in different subject populations, but our understanding of the phenomenon is still incomplete. For one thing, researchers have relied almost exclusively on the paradigm introduced by Ellsberg (1961), in which agents are offered bets on the color of a ball drawn (say a red ball or a blue ball) from urns whose composition is not fully specified. The simple binary choice structure of Ellsberg makes it easy to identify violations of SEU through violations of the "sure-thing principle" discussed above. But the artificial nature of the experiment may question the external validity of its findings. Despite its difficulty, designing choice environments that are more "natural," while providing clean identification, is an important task in the empirical literature on ambiguity aversion. We investigate deviations from SEU and MEU in financial environments, combining a novel experimental paradigm and measurement techniques that are inspired by recent work on revealed preference theory. We are also able to partially test for probabilistic sophistication.

Several recent papers propose how to do "revealed preference" analysis for SEU and MEU when researchers have dataset of choices under uncertainty (Chambers et al., 2015; Echenique and Saito, 2015; Echenique et al., 2018). The idea in revealed preference analysis is to use subjects' choices to infer a preference relation over alternatives. Our contribution is that we bring these theoretical apparatuses to the actual data of choice under uncertainty.

A standard model in economics and finance assumes that an agent chooses among possible portfolios of assets with uncertain payoffs, given prices and a budget for financial purchases. This setting naturally translates into our experimental design. Subjects in our experiment are asked to allocate "tokens" into two accounts (we call it the "market task"). Each account has an associated exchange rate which converts tokens into actual monetary rewards. These exchange rates define a budget set for a given decision problem. Two accounts correspond to two mutually exclusive events, and subjects are told that they will receive a payment based on the allocation and the realized event. Subjects faced two types of questions, which differ in the nature of two uncertain events. We generate uncertainty using two different sources. The first source is the classical Ellsberg-style urns and balls (called the "market-Ellsberg" task). The second source comes from simulated stock prices (called the "market-stock" task). We also ask the standard choice questions a la Ellsberg (1961) to identify whether the subjects are ambiguity averse or not (called the "Ellsberg-choice" task).

Our experimental design was implemented on two very different populations. One was a laboratory setting: we conducted seven experimental sessions at the Experimental Social Science Laboratory (ESSL) of the University of California, Irvine. A total of 127 subjects (age mean = 20.2, SD = 1.6; 35% male) participated in the study.[2] We refer to this data as "the lab." We also ran our experiments on a large-scale panel, the Understanding America Study (UAS) panel, a longitudinal survey platform representative of the U.S. population. We refer to this data as "the panel." In the panel, a total of 501 subjects (age mean = 51.9, SD = 15.4; 53% male) completed our study.[3] The market-Ellsberg task was administered only in the lab study.

By conducting experiments in settings that seek to mimic real-world investment problems, we expect to deliver greater external validity to standard tests of individual behavior in the face of uncertainty. In particular, it is possible that ambiguity aversion is significantly different in financial environments, compared to more artificial laboratory designs.

The observed choice data give us several "measures of rationality." First, we check whether subjects are maximizing "some" utility function. The question is whether the subjects make choices that are rational, meaning that there exists some subjective value (a utility function) to their choices that is maximized in their observed behavior. The test for utility maximization is the "generalized axiom of revealed preference" (GARP). GARP states that the agent's preferences revealed through choices do not exhibit cycles, ruling out a possibility of constructing a "money pump" to make money off the agent. If the agent's choices satisfy GARP, we can say that she behaved "as if" she maximized some (well-behaved) utility function. While a data either passes or fails GARP, it is useful to have an index for degree of violation. The Critical Cost Efficiency Index (CCEI) is one such index, measuring how much we need to relax the budget constraint for the data to be consistent with GARP, in other words "how close" the agent is to satisfying GARP.

Second, we check whether subjects are maximizing specific forms of utility function such as SEU and MEU. These tests are conclusive, meaning that the data either

[2] Three additional subjects participated in the study, but we excluded their data from the analysis. One subject accidentally participated in two sessions (thus, the data from the second appearance was excluded). Two subjects spent significantly longer time for each decision than anyone else.

[3] 263 additional subjects participated in the study, but they used devices other than desktop/laptop computers (mobile phones or tablets). Since their choices were noisier than the ones made by subjects using computers, we excluded their data from the main analysis.

passes or fails, but it is also possible that some data are "almost passing" and others are "definitely failing." As a final step, we calculate more fine-grained measures, the Critical Cost Efficiency Index (CCEI) and e_* (*minimal* e), that measure the degree of violation of GARP and SEU, respectively. Both of these measures examine on how close subjects behave to the economic theories.

To sum up, our experimental design is based on a new approach to testing theories of decision under uncertainty, and it seeks to capture the financial decision-making environments where the theory is commonly applied. The experiments were implemented in a formal controlled laboratory, and in a large-scale survey of a sample representative of the general U.S. population.

Results

The main purpose of our study was to test theories of decision under uncertainty. The news is not in favor of the theories. In our experiments, across lab and panel, the vast majority of subjects do not conform to SEU (Table 1). This finding would be in line with the message of the Ellsberg paradox, except that the pass rates for MEU are just as low as for SEU. In fact, in all of our samples, only one subject's choice is consistent with MEU but not SEU.

One positive finding is that subjects seem to be utility maximizers and do not violate Epstein's (2000) necessary condition for probabilistic sophistication. The test for utility maximization is the "generalized axiom of revealed preference" (GARP). Table 1 exhibits substantial pass rates for GARP, so that agents are consistent with the optimization of a utility objective. As for probabilistic sophistication, Epstein's criterion represents a necessary condition. So an agent that violates Epstein's criterion cannot be reconciled with probabilistic sophistication, but this does not mean that passing the test ensures consistency with the theory. Hence, our result on probabilistic sophistication really is inconclusive.

Table 1. Pass rates (%)

	GARP		SEU			MEU			PS	
Task	Type 1	Type 2	Type 1	Type 2	Joint	Type 1	Type 2	Joint	Type 1	Type 2
Market-stock	76.4	68.5	4.7	1.6	0.0	4.7	1.6	0.0	73.2	81.1
Market-Ellsberg	82.7	56.5	7.9	3.2	1.6	7.9	3.2	1.6	81.1	83.5

Includes subjects from the lab only. Note: Since Epstein's (2000) condition is only necessary for probabilistic sophistication (PS), the numbers reported here capture the upper bound of the fraction of the subjects who are consistent with probabilistic sophistication. Type 1 and Type 2 refer to the two types of question subjects faced in the experiment.

One might conjecture that the theories could be reconciled with the data if one allows for small mistakes, but our measures of the distance of the data to the theory (of the degree to which the data is rationalizable) do not suggest so. A more forgiving test is to check if price changes are negatively correlated with quantity changes: we refer to this property as "downward sloping demand," and it is related to SEU (see Echenique et al., 2018). Specifically, we consider the logarithm of the "change in quantity" (meaning the change in the amount purchased of an asset that pays off in one state) and the logarithm of the "change in prices." The downward sloping demand property says that the correlation between these changes is negative. An agent that complies with SEU will display a downward sloping demand: in fact, our test for SEU can be interpreted as a statement as to how precisely the downward sloping demand property should hold, or as the precise version of the downward sloping demand property that is equivalent to SEU (see Echenique and Saito, 2015).

The vast majority of subjects exhibit the downward sloping demand property, at least to some degree (meaning that the correlation between price and quantity changes is negative), but not to the extent needed to make them fully consistent with SEU, see Figure 1. The downward sloping demand property is strongly correlated with our measure of *distance* between the data and SEU, so there is a precise sense in which the degree of compliance with downward sloping demand can be tied to the violations of SEU.

Figure 1.

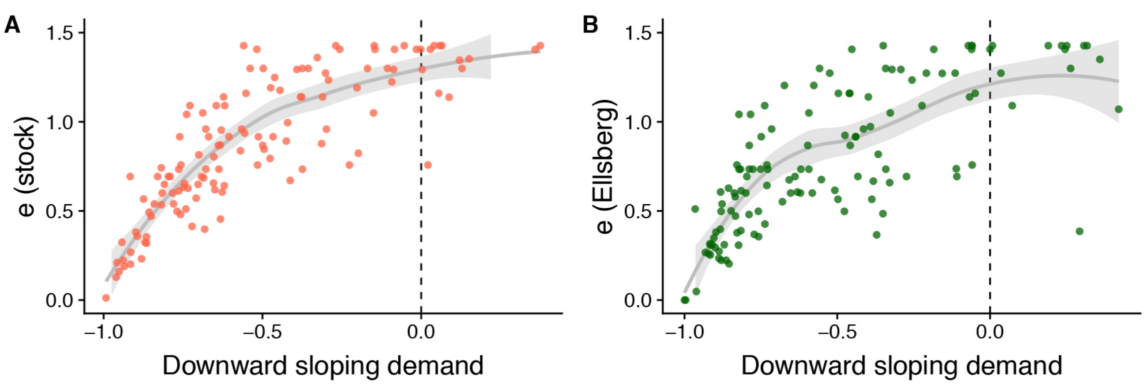


Figure 1: Relation between the degree of conformity to downward sloping demand and e in the market-stock task (A) and in the market-Ellsberg task (B) for subjects in the lab portion of the study. Gray lines represent LOESS curves together with 95% confidence bands.

Table 2. Distance measures

Task	Stat.	CCEI		e_*		
		Type 1	Type 2	Type 1	Type 2	Joint
Market-stock	Mean	0.9895	0.9868	0.6382	0.6381	0.8782
	Median	1.0000	1.0000	0.6004	0.6221	0.8675
	SD	0.0369	0.0382	0.4231	0.3883	0.3772
Market-Ellsberg	Mean	0.9925	0.9960	0.5964	0.5967	0.7985
	Median	1.0000	1.0000	0.6004	0.5390	0.7340
	SD	0.0299	0.0133	0.4126	0.3965	0.3943

The pass rates for SEU are very small, but it is possible that small mistakes could account for a subjects' violation of SEU. We turn to a formal measure of the severity of violations of SEU. Table 2 report e_* (minimal e), a measure of the degree of deviation from SEU theory proposed by (Echenique et al., 2018). The number e_* comes from a perturbation to the model that allows SEU to accommodate the data: It can be interpreted as the size of a utility perturbation that can rationalize the observed choices, or it can be interpreted as the magnitude of price-misperception that would be needed to make the data consistent with the theory. Thus, the number e_* is zero if a choice data is consistent with SEU, meaning that no perturbation is needed to rationalize the data by means of SEU, but takes a strictly positive value if the data violates SEU. The larger is e_*, the larger is the size of the perturbation needed to rationalize the data by means of a perturbed version of SEU (Echenique et al., 2018).

As can be seen in Table 2, the magnitudes e_* of are substantial. On the one hand, e_* is clearly correlated with downward sloping demand—indicating that the degree of violations of SEU can be understood through the downward sloping demand property. On the other hand, it is clear that the magnitude of perturbations that would be needed to accommodate the data is substantial.

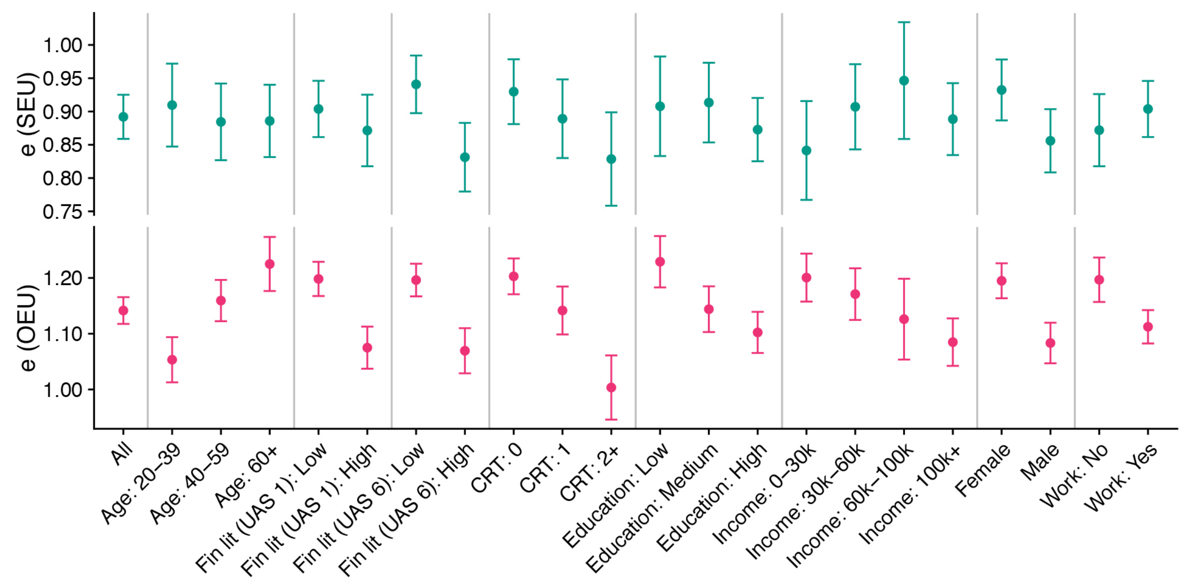
As indicated before, the picture is rosier when we simply look at utility maximization. The pass rates for GARP, the test for utility maximization, are substantial. The conclusion does not change when we look at how far the subjects who do violate GARP are from rationality.

The Critical Cost Efficiency Index (CCEI) is a measure of the degree of compliance with GARP. It is heavily used in the recent experimental literature to gauge how close subjects are to being rational economic agents. In our lab data, the average CCEI is higher than 0.98, which implies that, on average, budget lines needed to be shifted down by about 2% to eliminate a subject's GARP violations (Table 2).

Our panel experiment allows us to compare the distance to SEU with sociodemographic data. One of the main advantages of using the *Understanding America Study* (UAS) panel, is that we have access to multiple past surveys, in which subjects participated and we have access to the measurements and experiments performed by other researchers. As a consequence, we can use measures of cognitive ability measured with the Cognitive Reflection Test (CRT) and financial literacy. We can also use the results from an experiment on *objective* expected utility (OEU): meaning that the probabilities involved are known and given to the subjects. The OEU study we focus on (Carvalho and Silverman, 2017) shares important similarities with ours, in that subjects, who knew that two payoff-relevant states were equally likely to happen (50-50), had to choose portfolios of financial assets, subject to state prices and a budget.

Our results from the panel are reported in Figure 2 (top panel) and Table 3 (columns 1 and 2). The first notable finding is that age and e_* are not significantly correlated, which is in a stark contrast with previous findings as we discuss below. Second, we find that subjects with higher financial literacy score (measured in previous UAS module #6) have significantly smaller e_*, meaning that these subjects are significantly closer to SEU. However, there is no significant difference for distance to SEU as measured by the other financial literacy module (UAS module #1). Similarly, cognitive ability (measured by the score from the Cognitive Reflection Test) has a significant negative relation with the distance to SEU. Finally, we observe a significant gender effect. Male subjects made choices that are significantly closer to SEU compared to those made by female subjects. Education and employment status do not exhibit a significant effect on e_*.

Figure 2. Average e_* for each demographic category



Bars represent 95% confidence

These observations are confirmed by estimating a linear regression model estimating how close an individual is to economic theories (e_* for SEU and OEU for each subject) controlling for a set of sociodemographic characteristics.[4]

Regression results are presented in the first two columns of Table 3. First, it confirms our observation above, that there is no significant effect of age on e_*. The financial literacy variable measured in UAS module #6 (but not in UAS module #1) is significantly negatively correlated with e_* (i.e., subjects with higher financial literacy are significantly closer to SEU than subjects with low financial literacy), and its significant effect remains even after we control for education, income, and cognitive ability (column 2). Subjects in higher income brackets have significantly larger e_* (i.e., further away from SEU), compared to those in the lowest bracket in our sample. Educational background has an effect in the expected direction, but this is only significant in the category “associate or professional degree,” not in “college or post-graduate degree.”

[4] These explanatory variables include: age group (omitted category is “20-39 years old”), above-median financial literacy (measured in UAS modules #1 and #6; omitted category is “below-median score”), cognitive ability measured with CRT (omitted category is “score is 0”), education level (omitted category is “high school graduate or less”), annual income group (omitted category is “less than $25,000”), gender, and employment status. The model is estimated by OLS with robust standard errors.

This set of results is in stark contrast with the findings reported for OEU in Echenique et al. (2018)—older subjects have significantly larger e_* for OEU (i.e., further away from OEU, not SEU) than younger subjects; a robust finding in the sense that it holds across data from three different panel surveys (Choi et al., 2014; Carvalho et al., 2016; Carvalho and Silverman, 2017). The three OEU panels exhibit the same pattern. Since the survey of Carvalho and Silverman (2017) was administered on the same panel as ours, the UAS, we calculate average e_* using the set of demographic variables as above and also run the same set of regressions. In their data, we observe that e_* for OEU are significantly correlated with age, financial literacy, cognitive ability, education level, employment status, and gender (Figure 2, bottom panel; columns 3 and 4 in Table 3). These results indicate that compliance with SEU and OEU may be unrelated.

A subset of our sample participated in a separate experiment (Carvalho and Silverman, 2017) that tested for the model of objective expected utility, where the agent chooses so as to maximize the expected value of her utility, where the expectation is calculated according to the objectively given probabilities. Using this subsample, we replicate the usual demographic effects of age, education, cognitive ability and financial literacy. Our results suggest that SEU and OEU may be unrelated phenomena. Situations where agents are provided with objective probabilities may be viewed, and reasoned about, by agents in substantially different ways than situations with uncertainty.

One final implication of our results is worth discussing. Our experiments included a version of the standard Ellsberg question. The distance to SEU captured by e_* is not strongly related to the ambiguity attitude identified from the choice pattern in the standard Ellsberg-choice task. The experiments included a treatment on the variability of the uncertain environment, especially the variability in the sample paths of the stock price whose outcomes subjects were betting on. Subjects who were exposed to more variable uncertainty seems less ambiguity averse than subjects who were exposed to less variable uncertainty.

Conclusion

Motivated by recent theoretical advances, providing revealed-preference characterizations of expected utility theory, we design and implement a novel experimental test of the theory. We find that subjects respond to price changes in the expected direction (they satisfy the downward sloping demand property, at least to some degree), but not enough to make their choices consistent with SEU. Our findings are the same, regardless of whether we look at lab or panel data. In fact, there is a striking similarity in how SEU is violated across the two studies. The subject populations are very different, but look very similar in terms of the distribution of the degree of violation of SEU.

Motivated by the literature on ambiguity aversion, we study the possibility that violations of SEU are due to ambiguity aversion, and look at whether maxmin expected utility (MEU) can explain the data. MEU adds no explanatory power to SEU, with a single exception, all subjects who fail to satisfy SEU also fail MEU. It is possible that other models of ambiguity aversion could do a better job of accounting for our experimental data. We are restricted to MEU because it is the only model for which there exists nonparametric tests of the kind that we use in our paper; it is also arguably the best known, and most widely applied, model in the ambiguity literature. The testable implications of other models of ambiguity-averse choice is an interesting direction for future research.

Finally, the results in our experiments are markedly unaffected by some of the demographic characteristics that other studies on risky choice (not uncertain) have found significant. Older subjects do not seem to violate SEU to a significantly larger degree than younger subjects. Neither do we see significantly higher degrees of SEU violations in our broad sample of the U.S. population, compared to our laboratory experiment conducted on undergraduate students. However, financial literacy appears to be significantly associated with subjects' distance to SEU—although this significant correlation is only evident in one of the financial literacy measurements in the panel. There are modest effects of income and education. Together with the finding that the distances to OEU and SEU seem to be largely unrelated, our results suggest that behavior in the presence of uncertainty is fundamentally different from risk.

Our objective has been to understand empirically economic theories that can serve as a normative guide in financial decision making. The theories are not only used by economists in their models, but can also be useful in formulating financial recommendations. To this end, we have tried to embed our experiments in natural financial settings. There is no doubt that further studies are necessary to fully understand the behavior in environments that are more “natural” than traditional artificial Ellsberg-style settings. Our non-parametric-revealed preference tests and the empirical approach driven by these theories should hopefully be a useful tool to collect more evidence in this direction.

Table 3. Relationship between demographic characteristics and e_*

	e_*(SEU)		e_*(OEU)	
	(1)	(2)	(3)	(4)
Treatment: Large	0.023	0.016		
	(0.034)	(0.034)		
Age: 40-59	-0.023	-0.012	0.129***	0.130***
	(0.044)	(0.045)	(0.027)	(0.028)
Age: 60+	0.023	0.026	0.215***	0.208***
	(0.048)	(0.048)	(0.034)	(0.035)
Fin. lit. (UAS #1): High	0.052	0.034	-0.056	-0.058
	(0.041)	(0.043)	(0.030)	(0.031)
Fin. lit. (UAS #6): High	-0.117**	-0.106**	-0.074*	-0.070*
	(0.042)	(0.041)	(0.030)	(0.031)
CRT score (UAS #1): 1	-0.021	-0.013	-0.038	-0.040
	(0.040)	(0.040)	(0.028)	(0.028)
CRT score (UAS #1): 2+	-0.052	-0.059	-0.122**	-0.122**
	(0.050)	(0.051)	(0.037)	(0.038)
Education: Some college		0.046		-0.040
		(0.053)		(0.035)
Education: Assoc. or professional degree		-0.107*		-0.062
		(0.054)		(0.038)
Education: College or postgraduate		-0.015		-0.021
		(0.050)		(0.037)
Income: 25,000-49,999		0.109		0.057
		(0.059)		(0.035)
Income: 50,000-74,999		0.184**		0.033
		(0.058)		(0.040)
Income: 75,000-149,999		0.155**		0.007
		(0.060)		(0.039)
Income: 150,000+		0.124		0.041
		(0.085)		(0.058)
Male	-0.052	-0.062	-0.082**	-0.084**
	(0.036)	(0.036)	(0.025)	(0.025)
Working	0.053	0.024	-0.006	-0.014
	(0.040)	(0.040)	(0.027)	(0.029)
Constant	0.923***	0.838***	1.173***	1.183***
	(0.051)	(0.070)	(0.031)	(0.038)
Observations	490	490	1,377	1,367
R^2	0.036	0.070	0.073	0.077
Adjusted R^2	0.018	0.039	0.068	0.066

Robust standard errors are presented in parentheses. *p<0.05, **p<0.01, ***p<0.001.

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