



## Revealing risky mistakes through revisions

Zachary Breig<sup>1</sup> · Paul Feldman<sup>2</sup>

Accepted: 6 March 2024

This is a U.S. Government work and not under copyright protection in the US; foreign copyright protection may apply 2024

### Abstract

We argue that a choice that is modified, absent any informational change, is revealed to have been a mistake. In an experiment, we allow subjects to choose from budgets over binary lotteries. To identify mistakes, which we interpret as deviations from an underlying “true” preference, we allow subjects to revise a subset of their initial choices. The set of revised decisions improves under several standard definitions of optimality. These mistakes are prevalent: subjects modify over 75% of their initial choices when given the chance. Subjects make larger mistakes when inexperienced and when choosing over lotteries with small probabilities of winning.

**Keywords** Mistakes · Risk preferences · Uncertainty · Revealed preference · Expected utility · Experiment

**JEL Classification** C91 · D81 · D91

---

We are very grateful to David Arjona Rojo, Soo Hong Chew, Paul Ferraro, Andrei Gomberg, Kenan Kalayci, Edi Karni, Jim Murphy, John Quah, Karl Schlag, Tom Wilkering, and an anonymous referee for their helpful comments. The experiment described in this research was registered in the AEA RCT registry (AEARCTR-0004572). This study was approved by the University of Queensland Business, Economics & Law, Low & Negligible Risk Ethics Sub-Committee and funded by the National Science Foundation's dissertation grant #1824121. *Mistakes* are ours.

---

✉ Paul Feldman  
paul.feldman@ag.tamu.edu

Zachary Breig  
z.braig@uq.edu.au

<sup>1</sup> School of Economics, The University of Queensland, St. Lucia, Australia

<sup>2</sup> Department of Agricultural Economics, Texas A&M University, 600 John Kimbrough Blvd., Agricultural and Life Sciences Building, College Station, TX 77843-2124, USA

## 1 Introduction

Mistakes are integral to decision making. Parents tell their children to learn from their mistakes, and political leaders tell their constituents that “mistakes were made.” In academic contexts, researchers sometimes refer to failures to optimize some particular objective or adherence to a “biased” decision rule as a mistake. However, this goes against the canonical approaches of revealed preference, and decision makers often may not agree that their choices are mistakes. This, then, raises our research question: how can a researcher identify mistakes when underlying preferences are not known to the researcher *a priori*?

We propose and carry out a methodology to study mistakes, which we define as deviations from the decision maker’s true preferences. Specifically, we argue that if a choice is revised *without any new information or change in circumstances*, then either the initial choice or the revision is revealed to be a mistake. We use this intuition to study mistakes in a laboratory experiment. We find that when offered the chance to revise earlier choices, subjects overwhelmingly do so. Subjects’ revised choices are better according to every normative measure we employ, which we interpret as evidence that the initial choices were mistakes. This improvement in normative measures also implies that standard models of stochastic choice cannot explain the revisions. We then study how the characteristics of decision problems affect the prevalence of mistakes.

In our experiment, 181 undergraduates at the University of Queensland make choices over binary lotteries. Following Andreoni and Harbaugh (2009), subjects trade off the chance of receiving a prize against the size of that prize. If the subject does not receive the prize, they receive only the show-up-fee. Subjects face a linear budget, which implies that increasing the likelihood that they receive the prize by one percentage point decreases the size of the prize by a dollar amount that is constant within each budget. Our subjects know they will choose over the same 25 budget sets twice. Subjects are informed about the complete set of budgets and that any of these 50 tasks can be chosen for payment. After choosing from these 50 budgets, subjects learn that they will revise a random subset of thirty-six of their initial choices. Revision choices feature a  $2 \times 2$  within-subject treatment that changes the presentation of the tasks. One dimension of treatment adds a reminder of what was initially chosen, while the other dimension allows the subject to revise two choices from the same budget at the same time.

We find that when given a chance, subjects consistently revise their earlier choices. Over 75% of choices are revised, and 176/181 of subjects make at least one revision. Moreover, a majority of these revisions are meaningful: over 40% of revisions shift at least 10% of a subject’s budget from one good to the other.

Revisions, when compared to the initial set of choices, improve consistency with a number of normative criteria. First, revisions decrease the number of violations of first-order stochastic dominance (FOSD). Second, revised choices are closer to being rationalized by a well-behaved utility function and a well-behaved utility function that satisfies FOSD. Third, this relationship is preserved over the conventional functional families of expected utility and probability weighting.

Fourth, revised choices are more likely to be consistent with risk aversion. Finally, making identical choices across repetitions of the same budget increases for revised choices, although this type of stationarity only increases when both choices on the same budget are revised on the same screen. Given that either the original choices or their revisions are mistakes, the fact that revisions are more consistent with optimizing behavior, regardless of how much structure is placed on preferences, suggests that the initial choices are mistakes.<sup>1</sup>

Given that revisions indicate that initial choices contained mistakes, as a proof of concept we show that revisions can be used to study the drivers of mistakes. In particular, we study under what conditions these mistakes are made. First, the type of revision opportunity that subjects face affects revision behavior. We find that giving a subject a reminder about the choice they made earlier decreases the likelihood that they make a revision by 17 percentage points while offering them the chance to revise two choices at once increases the chance of making a revision by just under three percentage points. Second, choices the subject makes at the beginning of the experiment are more likely to be revised than those they make later. Third, the effect of decision times on revisions is nuanced. Controlling for subject fixed effects, the amount of time spent making a choice is positively correlated with the size of revisions, but this correlation is driven by the *negative* correlation between experience and time spent. Finally, subjects tend to make more and larger revisions when the budget set contains only lotteries with low probabilities of receiving a monetary prize.

There are several rival explanations for revisions that are unrelated to mistakes. We address them here. First, under a pay-one-choice-at-random mechanism, individuals may want to build a portfolio with their choices. Since revisions *replace* earlier choices, portfolio-building cannot explain any difference between choices and revisions. Second, subjects may be indifferent between both choices and revisions. Because the revised sets have higher normative indices, this seems unlikely. Third, choices and revisions may differ due to randomness from the decision-maker. Some choices may be random. However, the distribution of revisions is distinct from the distribution of initial choices as indicated by the improvement in our normative benchmarks. Hence, choice sets cannot be explained by a *stable* stochastic choice function (one that does not change throughout the experiment). Fourth, subjects may revise because they believe they are expected to. Such experimenter demand effects are improbable because of the neutral framing of revisions.<sup>2</sup> This is in stark contrast with other approaches where subjects are directly confronted with their inconsistencies or arguments about how choices *ought* to be made. Our subjects are simply asked what they would like their revised choice(s) to be, half the time with a reminder of their initial choice(s). Finally, a dual-self model—one “self” makes the original choices

<sup>1</sup> One may wonder why a violation of these normative measures is not itself an indication of a mistake. While this is likely true for violations of dominance, revisions may reveal mistaken choices even when the option chosen is not dominated. Measures relying on transitivity only reveal that there is a mistake in a *set* of choices and do not show *which* choice is a mistake.

<sup>2</sup> Furthermore, as we note in Section 6.2, much of the apparent improvement in decision making occurs before the revisions stage of the experiment. Thus, it cannot be the request to revise decisions that leads to these changes.

and another the revisions—could predict a difference (Fudenberg & Levine, 2006). Because revisions are completed in the same experimental session as the original choices, with only a few minutes separating choices from revisions, we consider it unlikely that multiple self models are reasonable explanations for our results.

What do we think explains these mistakes? Our main focus is to introduce an approach to identify mistakes—distinguishing between specific causal mechanisms is beyond the scope of this paper. Notwithstanding, we show how our methodology can be applied. For instance, problems that have a higher revision likelihood and magnitude of change are likely more difficult. In this way, we find that subjects take more time and are more likely to revise when the probabilities of winning are small.

Revisions can reveal the mistakes subjects make as a result of lack of experience. Subjects may be *learning* about their preferences and our interface after initially having chosen suboptimally. However, unlike standard strategic experiments, subjects do not learn the outcome of their choice in the *interim*, but only *ex-post*. Some potential initial confusion about the interface may have lead to 1.54% of the original choices being dominated. This drops to 0.91% by the revisions stage of the experiment. There are many meaningful contexts, such as investing for retirement or purchasing health insurance, in which this type of unfamiliarity likely contributes to mistakes (Choi et al., 2011; Bhargava et al., 2017).

Mistakes can be a costly part of everyday decision making. A large and growing literature documents ostensible mistakes in the financial domain: Individuals do not efficiently use or pay off their credits cards (Ponce et al., 2017; Gathergood et al., 2019), make sub-optimal mortgage choices (Agarwal et al., 2017), and under-react to taxes that are not salient (Chetty et al., 2009). The existence of mistakes across these domains, where objective decision quality can be assessed, suggests that individuals make mistakes in other consequential domains. Offering a chance to revise a decision may reveal these mistakes even when the researcher has no objective way to evaluate the choice.

The paper proceeds as follows: Section 2 discusses related literature. Section 3 presents the choice environment for binary lotteries. Section 4 describes the experimental procedures. Section 5 features our results contrasting sets of initial choices and sets of revisions using normative benchmarks. Section 6 explores the determinants of mistakes in the experiment. Section 7 features our final remarks.

## 2 Related literature

Identifying mistakes and where people make them is a key step in behavioral welfare economics (Bernheim & Taubinsky, 2018). Some have pointed out that with only weak assumptions on preferences, researchers can identify *mistaken beliefs* held by a decision maker (Koszegi & Rabin, 2008). Bernheim and Rangel (2009) and Bernheim (2016) argue that when choices made under different frames (or *ancillary conditions*) contradict each other, one may be able to use outside information to determine which choice to respect. One may think about our revision decisions as being from a particular frame, and our results show that choices made in that frame are more consistent with a variety of normative benchmarks. More generally, our

work is related to a contemporaneous literature that attempts to identify the decision maker's "true" preferences (Allcott & Taubinsky, 2015; Bernheim et al., 2015; Benkert & Netzer, 2018; Goldin & Reck, 2020). We complement this literature with a focus on understanding the mistakes themselves. Allowing subjects to revise is not new to our study, e.g., Kneeland (2015); instead, our novelty is using revisions to identify mistakes and the types of problems that lead to them.

We add to the literature on random choice. There is evidence that when making choices from the same choice set multiple times, subjects do not always make the same choice. This occurs both when the decisions are temporally close and when they are distant (Tversky, 1969; Hey & Orme, 1994; Hey, 2001; Birnbaum & Schmidt, 2015; Agranov & Ortoleva, 2017). In our experiment, all choices are made in a single sitting. Our design features revisions in addition to the more standard repetitions. These revisions *replace* subjects' earlier choices, implying that the difference between revisions and the initial set should not be due to subjects building a portfolio.

The use of revealed preference for the study of risk preferences in experiments is not unique to our study. Choi et al. (2007) uses revealed preferences to study consistency with rationality in a study where subjects choose between arrow securities using budgets. Halevy et al. (2018) employs the same data set and a separate experiment to correlate consistency with rationality to parametric fit using predicted behavior as a benchmark. Our revealed preference approach is closer to Polisson et al. (2020). They provide revealed preference tests for different functional specifications and use them to analyze the Choi et al. (2007) and the Halevy et al. (2018) data sets. We adapt their results to budgets over simple binary lotteries and use their finite-data revealed preferences' measures—adapted to various specifications—to reveal mistakes.

Prior research examines how violating specific norms is correlated with real outcomes and financial decisions. Jacobson and Petrie (2009) shows that subjects who make choices that are inconsistent with a class of theories of choice under risk do not choose optimally over non-experimental financial instruments. Choi et al. (2014) finds that experimental measures of rationality correlate with wealth and education. Rather than using predetermined normative criteria, our measure of a mistake is revealed by the decision makers themselves.

Other studies have considered choice behavior when choices can be objectively ranked, but these rankings must be determined by the decision maker through arithmetic calculation. Caplin et al. (2011) documents departures from full rationality and towards a satisficing heuristic in search problems. Kalayci and Serra-Garcia (2016) finds that adding complexity leads to choices that decrease overall payoffs. Gaudeul and Crosetto (2019) finds that adding this sort of complexity can induce the attraction effect in decision makers, but that they eventually make more informed decisions. Martínez-Marquina et al. (2019) finds that adding uncertainty impedes subjects' ability to maximize their payoff. Our identification of mistakes does not rely on there being an optimal choice that the experimenter knows, but the decision maker does not.

Recent work documents how decision makers reconcile potentially inconsistent prior choices. Benjamin et al. (2020) offers subjects hypothetical choices over retirement savings options and confronts them with choices that may be inconsistent. Nielsen and Rehbeck (2022) finds that subjects report a desire for their decisions over lotteries to satisfy several axioms and that a majority of subjects revise their

choices if they find that these choices violate the axioms. Yu et al. (2021) finds that a nudge causes subjects to revise their choices in a way that reduces multiple switching in a price list. The majority of the revision opportunities in our experiment did not give any indication to the subject that there were inconsistencies in their choices.

### 3 Choice environment

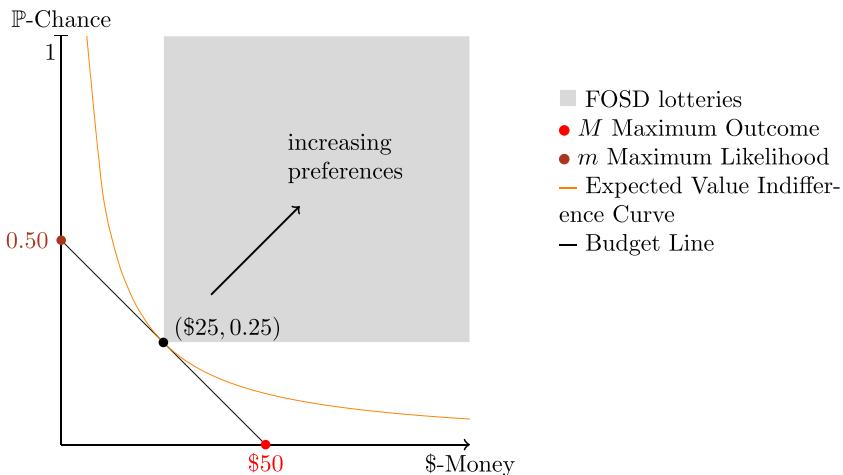
We begin this section by describing our choice environment and some properties of risk preferences. We then show how a decision maker with a canonical form of expected utility preferences makes choices in this environment. We conclude by discussing how we evaluate the concordance of sets of choices with various theories.

Preferences are defined over simple binary lotteries. A simple binary lottery is a lottery that has at most two outcomes, one positive outcome  $\$x$  with probability  $p$  and  $\$0$  with probability  $1 - p$ . Because one outcome is always  $\$0$ , we will abuse notation to represent each lottery by the pair  $(\$x, p)$ .

The choice problem involves a tradeoff between  $x$  and  $p$  using a linear budget. Each budget can be described by its maximum prize  $M \in \mathbb{R}_{++}$  and maximum probability  $m \in (0, 1]$ . Thus, any choice from the budget must satisfy  $x + \frac{M}{m}p = M$ , such that  $\frac{M}{m}$  is the “price” of increasing the likelihood of receiving the prize. With this construction, corner allocations on a budget line will always yield a certain outcome of  $\$0$ .

Figure 1 shows how we can plot lotteries, budgets, and increasing preferences using the familiar two-goods diagram. An expected value maximizer would maximize  $p \cdot x$ , leading to choices  $\$x^* = .5M$  and  $p^* = .5m$ . This highlights two features of expected utility: First, we may restrict attention to  $(x, p)$  without loss of generality, and second, any risk-neutral agents devote half their budget to  $x$ . If the decision maker is instead an expected utility maximizer with CRRA preferences given by  $u(x) = x^\alpha$ , it is straightforward to show that the budget shares the decision maker allocates towards probability and prize will be constant across budgets. Furthermore, any risk-averse (risk-tolerant) expected utility maximizer will allocate a budget share of more (less) than one-half to probability.

In our results, we will opt for non-parametric revealed preference tests. In particular, we will use Afriat’s theorem first to determine whether a utility function  $U(x, p)$  that is increasing, concave, and continuous can rationalize our data. Second, we will use a generalization of Afriat’s theorem (Nishimura et al., 2017; Polisson et al., 2020) that allows us to test for the ability of specific functional forms to rationalize our data and extend a standard measure of rationality. The functional forms we consider are expected utility ( $p * u(x)$ ) and generalized probability weighting ( $\pi(p) * v(x)$ ).



*Notes:* The decision maker faces a single budget with endpoints  $m = 0.5$  and  $M = 50$ . An expected value maximizer would choose the option  $(\$25, 0.25)$ , and the indifference curve that this point is on is given in orange.

**Fig. 1** Two-goods Diagram for Binary Lotteries

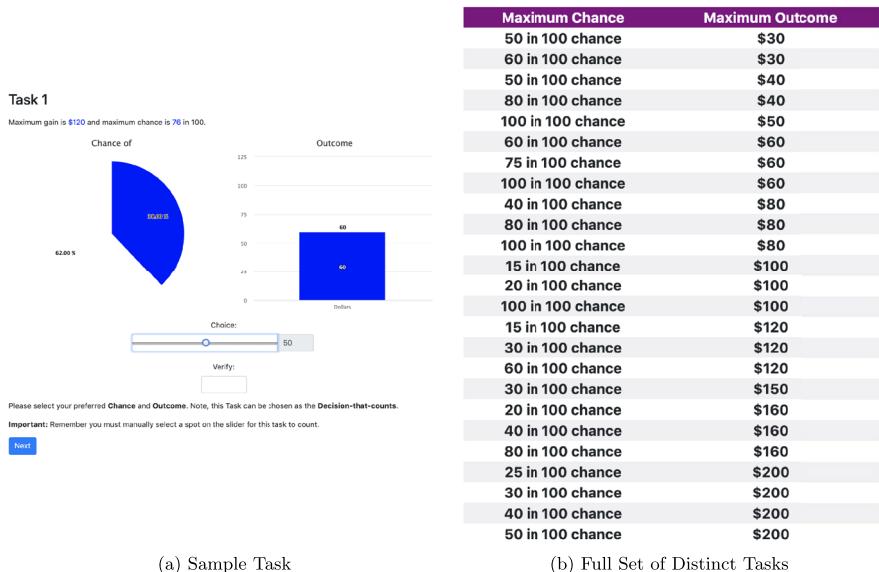
## 4 Experimental design

For each task, we elicit subjects' preferences over the set of binary lotteries—lotteries that give  $\$x$  with probability  $p$  and  $\$0$  otherwise—in a linear budget with endpoints  $\{M, m\}$ . The ratio of  $M$  to  $m$  gives the tradeoff between the size of the outcome and its likelihood. We emphasize three advantages of using this method. First, because budgets are linear in the  $(\$x, p)$  plane, most notions of consumer theory can be applied.<sup>3,4</sup> Second, because setting either  $\$x$  or  $p$  equal to 0 is strictly dominated, choices will typically be interior. This is beneficial because corner choices pose identification issues for budget-based methods. Third, in contrast to other linear budgets over lotteries (for example Feldman and Rehbeck (2022) for probabilities or Choi et al. (2007) for outcomes), this method features variation in both the probabilities and the outcomes simultaneously. A sample task, as subjects saw it, appears in Fig. 2a.

Subjects select their preferred lottery from each budget using a slider. Before making each choice, no information is displayed on the subject's screen other than the maximum outcome and the maximum chance. Once a subject interacts with the slider, a pie-chart is used to represent probabilities and a bar-chart represents the

<sup>3</sup> Only compactness is necessary for revealed preference tests, see Nishimura et al. (2017) for a detailed explanation.

<sup>4</sup> This, of course, requires preferences to be monotonic in money and the probability of receiving money. This is an assumption we maintain throughout the paper.



(a) Sample Task

(b) Full Set of Distinct Tasks

*Notes:* Panel A shows a sample choice task. Panel B summarizes the full set of budgets as it was presented to our subjects.

**Fig. 2** Experimental Task Summary

positive monetary amount.<sup>5</sup> As the subject moves the slider to the right (left), the pie-chart increases (decreases) and the bar decreases (increases). Once a subjects has identified their preferred bundle, they confirm their selection by separately entering it in a box.

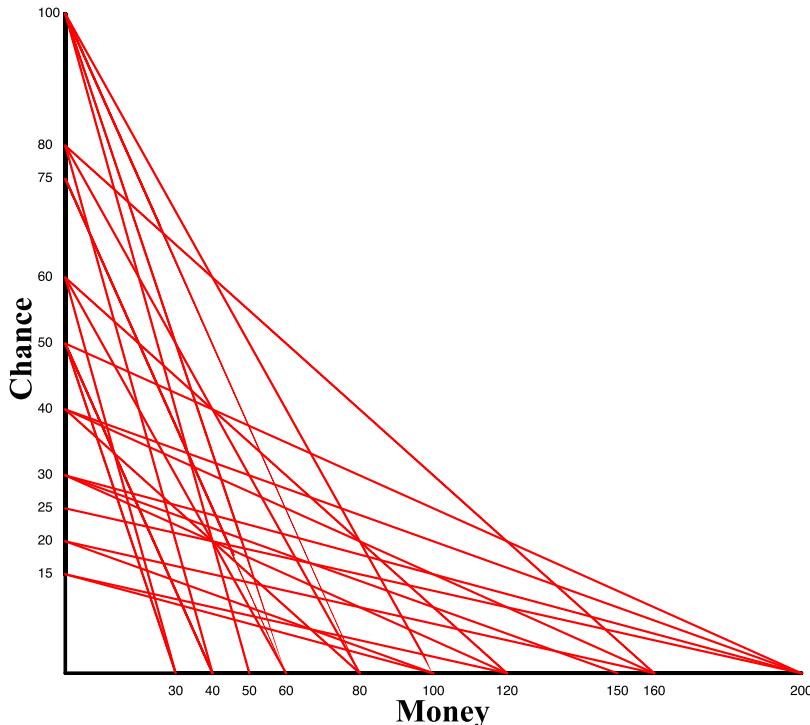
Figure 3 summarizes the budget sets used. The fact that the budgets cross allows for analysis of traditional rationality measures. The set also includes parallel budgets and pure price shifts to allow for analysis of income and substitution effects. A pre-analysis plan was submitted to the AEA RCT registry (AEARCTR-0004572) prior to the experiment and the visual interface was coded using oTree (Chen et al., 2016).<sup>6</sup>

One hundred and eighty-one University of Queensland undergraduates read the instructions on their computer terminal while the experimenter read the instructions aloud. Before starting the main part of the experiment, subjects completed three sample tasks.<sup>7</sup> These examples familiarize the subjects with how the slider affects positive outcomes, chances, and the tradeoff between them. The experiment itself has two parts: repetitions and revisions.

<sup>5</sup> Consistent with evidence imported from psychology, we present probabilities as natural frequencies and provide visual aids to facilitate ease of comprehension (Garcia-Retamero & Hoffrage, 2013; Hoffrage et al., 2000).

<sup>6</sup> A link to the pre-analysis plan and a discussion of changes to our empirical strategy appear in Online Appendix C.

<sup>7</sup> Sample tasks and the complete instructions appear in Online Appendix D.



*Notes:* This figure plots the full set of our experimental budgets. This figure was not displayed to subjects.

Dollars

**Fig. 3** Budgets

In Part I of the experiment, subjects made choices in 50 tasks. The 25 different budgets that were used were described to subjects by presenting them with a list of the pairs of maximum outcomes and chances during the instructions. The information, as subjects saw it, is summarized in Fig. 2b. Each subject chose from the 25 unique budgets followed by choosing from the same 25 budgets for a second time.<sup>8</sup> However, the order across subjects and for each block was random.

In Part II of the experiment, subjects revise 36 of the 50 choices they had already made. These revision tasks feature a  $2 \times 2$  within-subject treatment that changes the presentation of the tasks (see Table 1). The first change in presentation is the number of revisions they make within a revision task. Each revision task is either a “single” (in which the subject can revise a single earlier choice) or a “double” (in which the subject can revise two earlier identical tasks on a single screen). The second change

<sup>8</sup> Below, we describe how we allow subjects to revise some of their choices. Allowing subjects to choose from the same budget multiple times before any revisions are made allows us to understand whether any observed changes in decision-making between the original choices and the revisions were due to the subject being asked to revise or to the revision occurring after the original choice. We discuss the empirical differences between repetitions and revisions in Section 6.2.

**Table 1** Revisions by Type

	reminders	no reminders
single choice	6	6
double choices	12	12

*Notes:* Double choices featured the same choice problem twice over the same budget. Online Appendix D contains samples for each type of revision.

in presentation is whether or not subjects are given a reminder of the initial choice they made.<sup>9</sup> The subject faces six screens in each condition, leading to 36 revised choices. No single task is revised twice, and at least one task is revised from 24 of the 25 unique budgets. The order of treatments is randomized at the subject level.

To incentivize choices, one choice was selected at random from either the 36 revised choices or the 14 unrevised choices. Because subjects do not have the opportunity to revise *all* of the original 50 choices, they are incentivized to truthfully report their preferences each time they make a choice. Subjects made an average of 9.5 (19.5 s.d.) Australian dollars (AUD) and received a 10 AUD as a participation payment. Each of the experimental parts took around 30 minutes on average.

Table 2 provides summary statistics. Each of the 181 subjects made 50 choices in the first section of the experiment, for a total of 9050. Each choice is the portion of the budget (out of 100) which is allotted to increasing the probability of receiving the prize. The average choice was to devote just over 54% of their budget towards probability, indicating mild risk aversion. Subjects spent an average of roughly 24 seconds per task on the first 50 tasks.

Each subject faced 36 revisions problems, for a total of 6516. We say that the subject made a revision if their revision choice differs from their initial choice. When given the choice, subjects make revisions roughly 75% of the time. The size of the revision is the difference in the portion of the budget assigned to probability between the initial choice and the revision. These revisions are on average near zero (indicating that revisions are not on average significantly more or less risky than the initial choices). However, the average absolute value of the revision is nearly 12, indicating that subjects are on average shifting more than 10% of their budget from prize to probability (or vice-versa).<sup>10</sup>

<sup>9</sup> For revisions with reminders, subjects are shown a pie-chart and bar graph that matched their prior choice. The pie-chart and bar graph are replaced with representations of their current choices as soon as they click on the slider. However, a line of text describing their prior choices remains. For all other choices, the initial graph was empty and the additional line of text is not provided.

<sup>10</sup> Camerer (1989) reports the results of an experiment in which subjects were allowed to revise their choices after the decision which counted was selected but before the gamble's outcome was reported. Only 2 of 80 subjects changed their decision in this case. These stark differences is likely due to the size of the number of choices in the choice set. Camerer (1989) has two alternatives for every choice while we have 101 alternatives.

**Table 2** Summary Statistics

Variable	Obs	Mean	Std. Dev.	Min	Max
Original Choice	9050	54.297	20.746	0	100
Seconds on Page	9050	24.024	17.661	3	375
Made Revision	6516	.752	.432	0	1
Revision	6516	.127	19.581	-100	100
Abs. Revision	6516	11.977	15.491	0	100

*Notes:* Original Choice is the percentage of the budget allocated towards probability. Seconds on page is the number of seconds a subject spent on one of the 50 original choice tasks. Made revision is a binary variable which is equal to one if the subject revised their original choice. Revision is the change in the percentage of the budget allocated towards probability. Abs. Revision is the absolute value of revision.

## 5 Do mistakes have normative content?

This section examines whether the mistakes we identify are “poor” choices. To decide whether choices are indeed worse, we evaluate them according to traditional normative benchmarks. The first benchmark is picking strictly dominated alternatives (violations of monotonicity), the second benchmark is rationalizability by an increasing utility function, the third benchmark is consistency with various functional forms (including expected utility), the fourth benchmark is consistency with risk aversion, and the fifth benchmark is whether behavior across repetitions is stationary (i.e., choices do not vary across the repetitions).<sup>11</sup>

Some of the indices and measurements that we compute below are known to depend on the size of the choice set that they are computed for. For example, given a fixed set of choices, adding an additional budget and associated choice must always weakly decrease the choice set’s Afriat Index (AI). For this reason, all of our comparisons are made across sets of 50 choices. We refer to the “initial” set as the first 50 choices that the subject made, while the “revised” set consists of the 36 revisions and the 14 choices that were not randomly selected to be revised.

### 5.1 Monotonicity

We find that 32/181 subjects violate monotonicity by selecting a corner—a certain outcome of zero—on at least one budget for their initial set of choices. In contrast, 17/181 subjects violate monotonicity when we look at their revised sets of choices.

<sup>11</sup> The primary focus of this section is comparing choices to revisions. Additional empirical results about these benchmarks can be found in A.2.

The mean number of corners chosen in the initial 50 budget sets is 0.768, while the mean number of corners in the revised set of 50 choices is 0.525.<sup>12</sup> Furthermore, only three subjects increase the number of corners chosen in their revised set, while 29 subjects decrease the number of corners chosen.

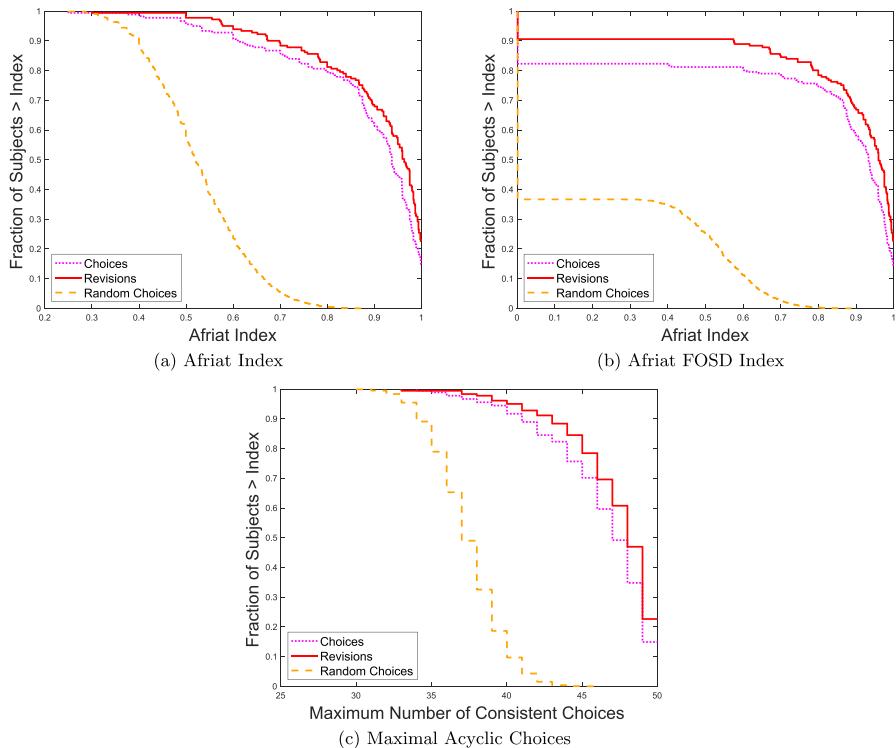
## 5.2 Rationalizability with an increasing utility function

The next benchmark which we use to compare choices to revisions is rationalizability. Following Afriat (1967) and Varian (1982), we define a set of choices to be rationalized if there exists a utility function which the choices maximize. Because every data set can be rationalized by a utility function (e.g., the constant utility function), we further place the restriction that the utility function which is maximized must be increasing.

Because this rationality test has a binary outcome, it is common to use a more continuous measure. The measure of rationalizability we employ is Afriat's Index, which is a number  $e$  between zero and one (Afriat, 1973). Mathematically, a lower index reduces the number of restrictions that a utility function has to satisfy: Rather than requiring the utility from bundle  $(x_i, p_i)$  to be higher than the utility from all bundles which satisfy  $x + \frac{M_i}{m_i}p \leq M_i$ , the utility need only be higher than all bundles which satisfy  $X + \frac{M_i}{m_i}p \leq eM_i$ . The AI for a set of choices is the highest  $e$  for which the choices are rationalized. This index has become a common measure for how far a set of choices is from being rationalized (Andreoni & Miller, 2002; Choi et al., 2007; Polisson et al., 2020).

In our context, there are two relevant types of monotonicity. The first is monotonicity in the classic sense: The decision maker strictly prefers a bundle which is strictly higher in one dimension and no lower in any other dimension. In this case, we use the Afriat Index as it has been classically defined for any collections of choices from linear budget constraints. Our stronger notion of monotonicity is first-order stochastic dominance. This places the same restrictions as standard monotonicity, but also requires that the decision maker never chooses on the endpoints of the budget line (because any interior choice first-order stochastically dominates the endpoints, which guarantee a payoff of zero). When using FOSD as the notion of monotonicity, a set of choices is assigned an index of zero if it includes any choices on the endpoints of the budget line. Otherwise, it is equal to the standard Afriat Index.

<sup>12</sup> Dominated choices are relatively rare in our experiment as compared to other experimental work with convex budgets. In the symmetric treatment of Choi et al. (2007), 44/47 subjects made at least one dominated choice, and over 13% of choices were dominated. Choi et al. (2014) used a design similar to that of Choi et al. (2007) with a representative sample of households in the Netherlands, and of their subjects 1149/1182 made at least one dominated choice and 33% of choices were dominated. One possible reason dominated choices are more common in the design of Choi et al. (2007) is that in their choice sets a larger portion of options is dominated.



*Notes:* These figures contain our main rationality results using Afriat's index (Panel a), Afriat's index under FOSD (Panel b), and maximal transitive relation (Panel c). Each panel contains the fraction of subjects whose rationality index is greater than the x-axis value for their initial choices, their revised choices, and a uniformly random choice rule ( $n=10,000$ ).

**Fig. 4** Rationalizability for Initial Choices and Revised Choices

The Afriat indices and Afriat indices under FOSD can be found in Fig. 4a and b, respectively. The figures also contain the Afriat Index for a uniform random choice rule that measures the power of our design to detect violations of rationality (Bronars, 1987).<sup>13</sup> Clearly, both the Afriat and Afriat FOSD indices of the revised sets of choices first-order stochastically dominate the distributions from the initial sets of choices. Revised decisions are closer to being rationalized by a utility function, indicating that some of the initial decisions may have been of poor quality.

We also report another consistency measure for the maximum acyclic set—the maximum number of choices that could be rationalized by an increasing utility function (Houtman & Maks, 1985; Demuynck & Rehbeck, 2023). This measure appears

<sup>13</sup> Choices on the budgets were discretized to 101 distinct choices that are equidistant on each budget. Our uniform random rule randomizes over the options on a budget subjects could make. This discretization leads to a strictly positive probability (2 out of 101) of a budget endpoint being chosen, which in turn leads to over half of all simulated subjects making at least one dominated choice.

in Fig. 4c and does not alter the result that the consistency of revised choices is always higher for any fraction of subjects.

Our general rationalization results are as follows. For their initial choices, 80 subjects have an Afriat Index of at least 95%, 76 subjects have an FOSD consistent Afriat Index of at least 95%, and 95 subjects have their maximum number of consistent choices greater than 47. For their revised choices, the number of consistent subjects increases across all three benchmarks to 100, 99, and 113, respectively. Median consistencies for the initial choices are 94%, 93%, and 47, compared to 96%, 96%, and 48 for the revised choices, across the three benchmarks.<sup>14</sup> A signed rank test rejects ( $p < .01$ ) equality of distributions between initial choices and revised choices for the three benchmarks. Hence, the number of subjects whose choices can be rationalized by some utility function is unambiguously larger for revised choices as implied by these metrics and Fig. 4. Mean consistencies for the initial choices are 88% (15% s.d.), 76% (36% s.d.), and 46 (4 s.d.), compared to 90% (13% s.d.), 84% (29% s.d.), and 47 (3 s.d.) for the revised choices, across the three benchmarks.

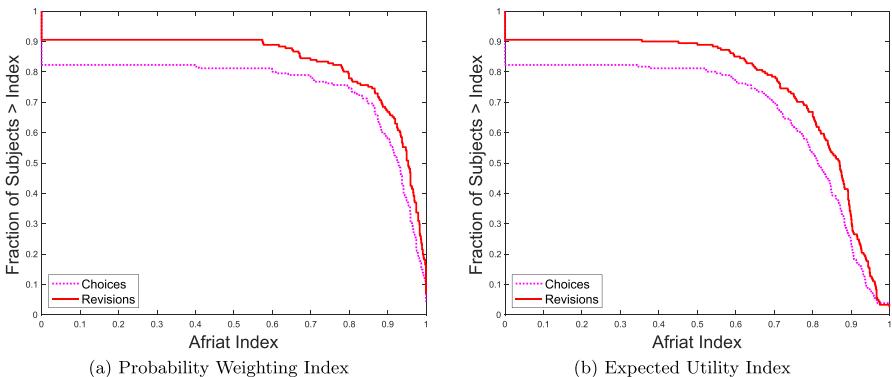
### 5.3 Consistency with common utility functions

An additional means of evaluating a subject's choices is to establish whether those choices are consistent with a specific normatively appealing utility representation, such as expected utility. Given recent developments in the theory of revealed preferences we can test these specific models of behavior. In particular, we adapt the results from Polisson et al. (2020) to our context, allowing us to measure consistency with these models. Essentially, a set of choices will have an index of  $e$  if  $e$  is the minimum value such that there exists a utility function from the specified family that assigns a utility to each bundle  $(x_i, p_i)$  chosen from budget  $\{M_i, m_i\}$  that is higher than all bundles that satisfy  $X + \frac{M_i}{m_i}p \leq eM_i$ . Formal details and results are collected in Online Appendix A.1.

The utility representations we consider are a generalization of Quiggin's (1982) cumulative probability weighting (PW) and expected utility (EU). PW is more general than EU because it allows for any non-identity probability functions. Moreover, PW is more general than Yaari's (1987) dual theory as we allow for any increasing utility function. Because each of these representations places additional restrictions on the previous one and all must satisfy the restrictions from Afriat's theorem, the PW index is lower than the Afriat FOSD index and the EU index is lower than the PW index.

The results for the indices can be found in Fig. 5a and b. The PW indices of the revised sets of choices first-order stochastically dominate the PW indices of the initial sets of choices. The EU indices of the revised sets of choices *almost* first-order stochastically dominate the EU indices of the initial sets of choices. Thus, when

<sup>14</sup> The distribution of Afriat indices is highly dependent on the budgets subjects are offered. This leads to difficulties in comparing distributions of these indices across experiments with different designs. However, the average of the Bronars Index can provide a baseline measure of how strict the Afriat Index is for a given set of budgets. The mean Bronars Index in our experiment is 52% and the mean Afriat Index is 88%. In Choi et al. (2007), the mean Bronars Index was 60% and the mean Afriat Index was 94%. Hence, Choi et al. (2007) has both higher rationality scores and weaker tests of rationality.



*Notes:* These figures sum up our main rationality results for probability weighting ( $\sum \pi(p_i)u(x_i)$ , Panel a) and expected utility ( $\sum p_i u(x_i)$ , Panel b). Each panel contains the fraction of subjects whose rationality index is greater than x-axis value for the initial choices and the revised choices.

**Fig. 5** Rationalizability Using Common Utility Functions

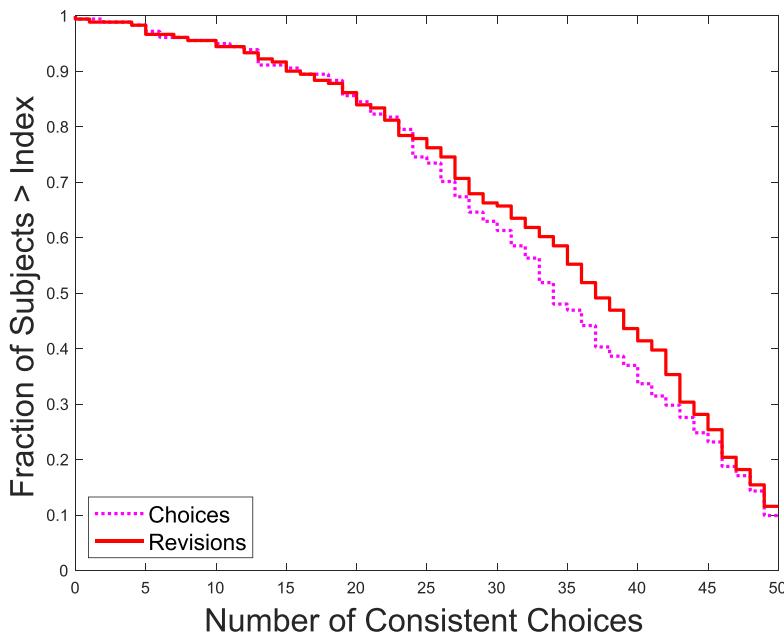
offered the chance, subjects revise their choices in a way that makes them closer to being consistent with commonly used representations.

Our rationality results for the two representations are as follows. For their initial choices, 68 subjects have a PW-consistent Afriat Index of at least 95%, and 14 subjects have an EU-consistent Afriat Index of at least 95%. For their revised choices, the number of consistent subjects increases for both specifications to 92 and 23, respectively. Median consistencies for the initial choices are 93% and 81% compared to 95% and 87% for the revised choices, for the two specifications. A signed rank test rejects ( $p < .01$ ) equality of distributions between initial choices and revised choices for the two specifications. The number of subjects whose choices can be rationalized by either a probability weighting or an expected utility representation is larger for revised choices as implied by these metrics and Fig. 5. The mean Afriat indices for initial choices are 75% (36% s.d.) and 68% (33% s.d.), compared to revisions which are 83% (29% s.d.) for probability weighting and 75% (36% s.d.) for expected utility.

## 5.4 Risk aversion

We also discuss a heuristic benchmark for risk aversion. Note that any allocation where the budget shares favor the outcome ( $x$ ) over the ( $p$ ) likelihood will be second order stochastically dominated by equal shares—the optimal allocation for an expected value maximizer. Therefore, any concave EU subject—or any risk-averse subject—can never select an allocation that places a greater budget share on the outcome.<sup>15</sup> Our benchmark counts the number of choices that are consistent with

<sup>15</sup> Note that for a subject to be risk averse it is not sufficient for  $U$  to be concave. For example,  $U(x, p) = \log(p) + 2\log(x)$  is concave and it represents the same preferences as  $V(x, p) = p * x^2$ , a risk tolerant utility function. For probability weighting both  $U$  and  $\pi$  must be concave for preferences to be consistent with risk aversion Hong et al. (1987).



*Notes:* This figure plots the fraction of subjects whose number of consistent risk-averse choices are greater than the x-axis value for both their initial choices and their revised choices.

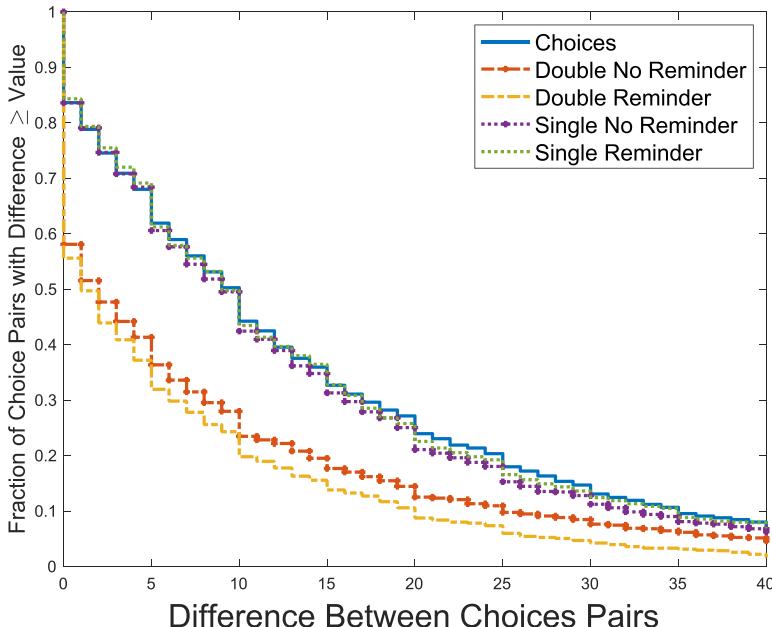
**Fig. 6** Number of Choices that are Consistent with Risk Aversion Across Subjects

FOSD and that place a greater budget share on the probability. As depicted in Fig. 6, this measure provides a benchmark for the maximum number of choices that can be consistent with risk aversion.

We find that 18/181 subjects do not violate risk aversion—on at least one budget—over their initial choices. Revisions lead to a slight increase in the number of subjects that do not violate risk aversion 21/181 at all. Fifty-one subjects increase the number of violations in their revisions, while 100 subjects decrease the number of violations. A signed rank test rejects the null hypothesis that the number of violations of risk aversion is the same across initial choices and revisions ( $p < 0.01$ ). The mean number of risk-averse choices from the initial choices is 33 (13 s.d.), while from revisions, the mean number of risk-averse choices is 35 (13 s.d.). Whether risk aversion is a normatively compelling criterion is a choice for the reader.

## 5.5 Stationarity

Next, we discuss the extent to which subjects were *stationary*, which we define as making the same choice across repetitions of a single budget. Only five subjects



*Notes:* This figure plots the fraction of choice pairs that are inconsistent with stationarity across our experimental treatments. The x-axis captures how far apart choices were across the repetitions in terms of the percentage of the budget allocated towards increasing the prize.

**Fig. 7** Non-Stationarity in Choice Behavior

were stationary across all of their choices.<sup>16</sup> 16.35% of subjects' initial pairs of choices were stationary. When pairing a revised choice in the single revision treatment with its unrevised paired choice, the two are only equal to each other in 16.02% of cases. When two revisions are made at a single moment, they are equal to each other in 43.14% of all cases.

Figure 7 plots the distributions of differences between pairs of decisions in these cases. It is immediate that allowing for a single decision to be revised does not necessarily mean that this revised choice will be any closer to its paired choice than the initial choice was—there is essentially no difference between the (Cumulative Density Functions) CDFs of differences between the initial choices and the single revision problems. On the other hand, there is a clear shift to the left of the distribution of differences when two choices are made at once. Signed-rank tests for equality of distributions of differences between initial sets and revised sets gives a  $p = 0.02$  for single revisions and  $p < 0.01$  for double revisions.

While stationarity may be normatively appealing, we emphasize that both expected utility and non-expected utility models can predict different choices across repetitions.<sup>17</sup> For instance, decision makers with a preference for randomization

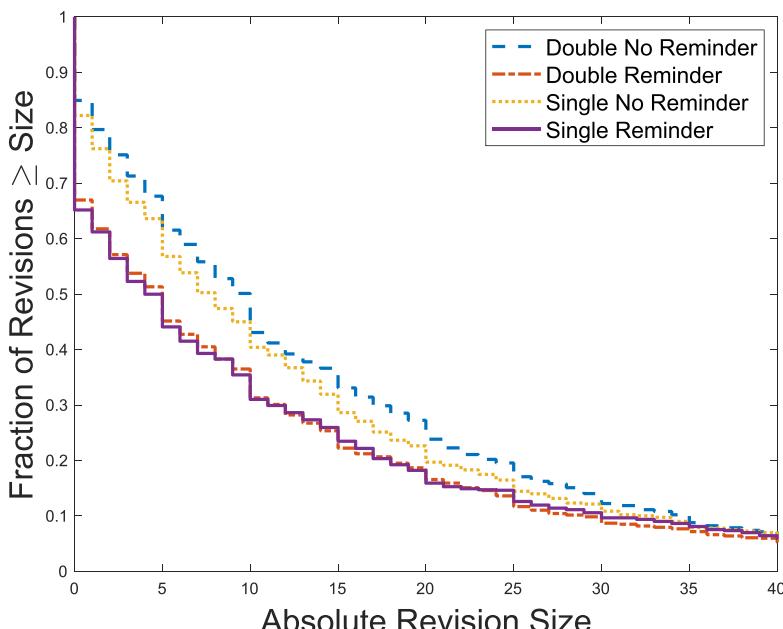
<sup>16</sup> These five subjects maximized expected value by choosing exactly in the middle of the budget line.

<sup>17</sup> An example with expected utility can be provided upon request.

would exhibit non-stationarity (Agranov & Ortoleva, 2017). An alternative hypothesis is that individuals may be susceptible to cognitive mistakes (Khaw et al., 2021). Drift diffusion models are an instance where the individual chooses their preferred alternative more frequently but, due to a stochastic error, may fail to do so (Ratcliff, 1978; Ratcliff & McKoon, 2008). Most of these cognitive models predict that experience will ameliorate mistakes. We suspect the cognitive explanation may be appropriate for repeated choices not made on the same screen. However, and consistent with the evidence for preferences for randomization, it is unclear why individuals would experience different cognitive difficulties with the same choice twice on the same screen.

## 6 Mistakes and their determinants

This section discusses the characteristics of the decision problems over which subjects made mistakes. As discussed previously, we label a decision a “mistake” if when given the chance to revise the decision without any new outside information, the subject decides to make a revision. Subjects were offered the chance to revise 36 of their 50 decisions. Just over 75% of the initial choices were revised when subjects



*Notes:* This figure showcases the relationship between the initial choices and the revised choices by measuring the distance between them. The curves represent the fraction of choices whose distance was greater than the x-axis value across the experimental treatments. The x-axis is measured in terms of the percentage of the budget allocated towards increasing the prize.

**Fig. 8** Absolute Size of Revisions

were offered the chance. These revisions could have made the decision less risky (a positive revision) or more risky (a negative revision). Revisions (whose units are percentages of the budget shifted towards probabilities) were on average near 0 (mean of 0.127 with clustered standard error 0.603). This indicates that subjects did not on average revise their decisions towards probabilities or outcomes.

Despite subjects not revising towards one direction or the other on average, the mean absolute value of revisions was 11.977 (clustered s.e. 0.634). This represents over 10% of subjects' budgets. This is not the result of a few outliers: Over 30% of choices had an absolute revision of at least 15.

## 6.1 Treatments and the likelihood of revisions

Figure 8 graphically represents the effects that treatments have on revisions. It shows the distribution of absolute revision size for each of the treatments. Offering subjects a reminder of their previous decision tends to make it less likely that they will revise that decision.

Table 3 shows the effects that treatments have on revisions in regression form. Columns (1) and (2) report how the likelihood of making a revision changes with treatments, while columns (3) and (4) show how the absolute value of revisions change with treatments. The treatment effects are consistent in all cases. Reminding subjects of what they chose previously both makes the subject less likely to revise and makes the average absolute revision smaller. Giving the subject two revisions at once makes subjects slightly more likely to revise and increases the size of revisions. The interaction of these treatments makes revisions less likely and the absolute size of revisions smaller, but only the latter of these effects is significant at the 10% level.

**Table 3** Treatment Effects

	(1) Made Revision	(2) Made Revision	(3) Abs. Revision	(4) Abs. Revision
Reminder	-0.17*** (0.022)	-0.17*** (0.022)	-2.27*** (0.63)	-2.21 *** (0.63)
Double	0.027** (0.013)	0.028** (0.013)	1.19** (0.60)	1.24 ** (0.61)
Reminder × Double	-0.0092 (0.022)	-0.0097 (0.022)	-1.30* (0.74)	-1.41* (0.75)
Constant	0.82*** (0.019)	0.83*** (0.026)	12.7*** (0.72)	13.3 *** (0.90)
Subject FE	No	Yes	No	Yes
Task FE	No	Yes	No	Yes
Observations	6516	6516	6516	6516

*Notes:* Linear regression clustered at the subject level. Each column represents a different regression, with the column head specifying the dependent variable. Significance indicated by: \*\*\*  $p < 0.01$ , \*\*  $p < 0.05$ , \*  $p < 0.1$ .

**Table 4** Experience and Learning

	(1) Made Revision	(2) Made Revision	(3) Abs. Revision	(4) Abs. Revision
Round	-0.00087** (0.00034)	-0.00088 (0.0013)	-0.071*** (0.015)	-0.21*** (0.058)
Round Squared		0.00000011 (0.000025)		0.0027** (0.0011)
Subject FE	Yes	Yes	Yes	Yes
Task FE	Yes	Yes	Yes	Yes
Observations	6516	6516	6516	6516

*Notes:* Linear regression clustered at the subject level. Each column represents a different regression, with the column head specifying the dependent variable. Significance indicated by: \*\*\*  $p<0.01$ , \*\*  $p<0.05$ , \*  $p<0.1$ .

## 6.2 Experience and learning

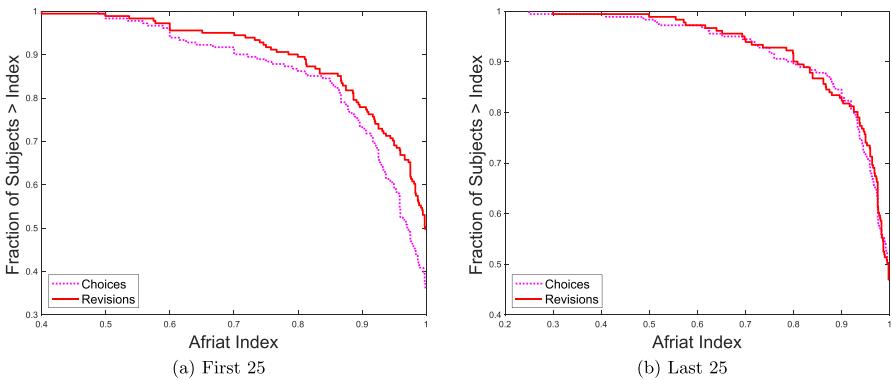
A natural hypothesis is that subjects should make fewer mistakes as they gain experience. However, this is not immediately obvious in this case as subjects in the experiment did not receive any explicit feedback.

Table 4 shows how revision behavior changes with the timing of the choice. The variable Round, which ranges from 1 to 50, is the round in which the original decision was made. Round may reflect the familiarity or experience the subject had with the choice environment. The results, which control for individual and decision problem fixed effects, show that more experienced subjects are less likely than less experienced ones to make choices that are subsequently revised, and the average size of their revisions are also smaller. Accounting for potential nonlinearities in the learning process, columns (2) and (4) show that while the effect of experience on making any revisions is close to linear, much of the effect of experience on the average size of revisions occurs in the early rounds.

Section 5 demonstrated that revised choice sets are meaningfully different from the original choice sets. However, the results about subject learning raise some interesting questions. In particular, it is still unclear whether revisions are different from the original choice *because they are revisions* or just because they were made with more experience.

To address this issue, we show that the evidence suggests experience is an important contributor to the difference between the original and revised choice sets. Panel (a) of Fig. 9 shows the distribution of Afriat indices computed for only the first 25 sets of choices and their revisions. This panel shows a similar pattern to that which was seen in Section 5.2: Revising choices from the first set of 25 budgets improves the associated Afriat Index on average. On the other hand, Panel (b) shows that revising choices from the second set of 25 budgets does not lead to a clear improvement in the associated Afriat Index.<sup>18</sup> This suggests that a majority of the improvements in normative measures may be driven by experience.

<sup>18</sup> A signed rank test rejects equality of the Afriat indices between original and revised choice sets generated from the first 25 budgets ( $p<0.001$ ). The same test does not reject equality of the Afriat indices between original and revised sets generated from the second 25 budgets ( $p=0.2813$ ).



*Notes:* These figures show the distribution of Afriat indices for partial choice sets. Panel (a) shows the distribution of Afriat indices for the first 25 choices subjects make along with the revisions of those choices. Panel (b) shows the distribution of Afriat indices for the second 25 choices subjects make along with the revisions of those choices.

**Fig. 9** Rationality and Experience

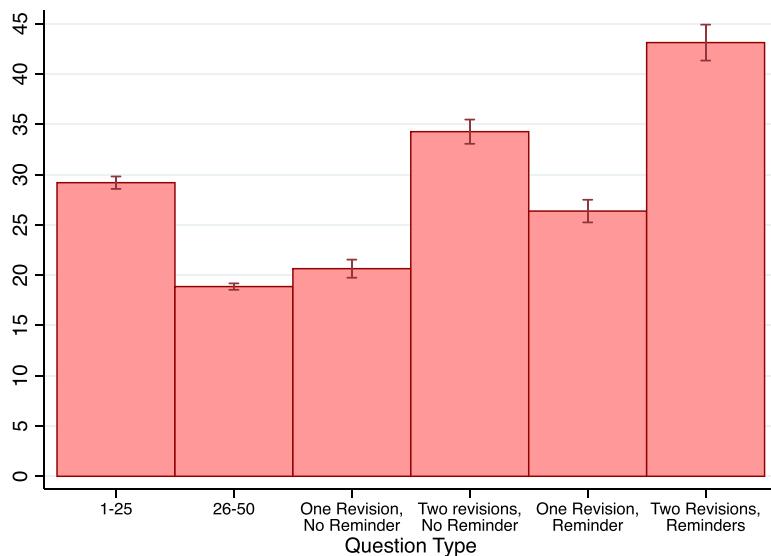
These results lead us to two methodological points for future research.

First, this implies that the differences between choices and revisions are not simply the result of experimenter demand effects. Despite our neutral framing, one might wonder whether the use of the word “revise” may subtly push subjects to think harder about the problem, leading to “better” decision making according to standard measures. This cannot be the case, because the decision quality of the second set of choices is almost indistinguishable from that of its revisions.

Second, our results suggest that researchers can learn about subjects’ mistakes without the machinery developed for this experiment. In our design, we are careful to explain that revisions *replace* earlier choices in order to rule out any incentives for portfolio-building. But because we show that experienced choices are not meaningfully different from revisions, future research can simply compare inexperienced choices to experienced ones in order to determine where mistakes are made. Indeed, it is already common practice for experimentalists to drop the first few choices subjects make in order to study those subjects’ “true” preferences. Our results support that practice and suggest that these dropped choices could be used to study the mistakes subjects make.

### 6.3 Decision times

The amount of time that subjects took to complete each type of problem can be found in Fig. 10. Single choices take less time than double choices over the same budget and on the same screen. Earlier choices and choices with reminders also take more time. The average time taken on the first portion of the experiment was just over 24 seconds per task.



*Notes:* This figure shows average time spent on a task's page for various decision types. The height of the bar gives the sample mean for each category of decision and the thinner lines give the 95% confidence interval for the mean.

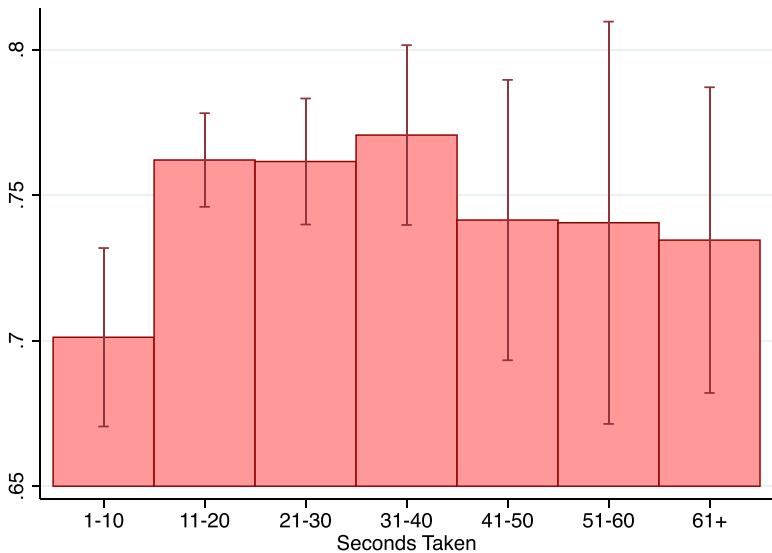
**Fig. 10** Time Taken by Decision Type

The likelihood of revision does vary with the time taken to make the initial decision. This can be seen in Fig. 11. The relationship appears to be nonlinear: Decisions that are taken very quickly are revised less often, but outside of this range time taken is negatively correlated with revision rates. However, this relationship is not causal. Because subjects are not randomly assigned to time taken, unobservable characteristics of the subject or decision problem may be driving the relationship between decision time and mistake rates.

The relationship between decision time and revisions is further explored in Table 5. The dependent variable in this table is the absolute size of revisions. Column (1) shows that over all observations, the amount of time spent on making a decision is uncorrelated with the amount that this decision is revised. However, Column (3) demonstrates that after controlling for both subject and task (i.e., budget set) fixed effects, there is a positive correlation between time taken and revision size.<sup>19</sup> This suggests that subjects who make decisions slower make smaller revisions, but that conditional on the subject, spending more time on a decision is associated with larger revisions.

Columns (2) and (4) of Table 5 additionally control for the round the decision is made in, which varies between 1 and 50. When controlling for the round, the relationship between time taken and the size of revision is both small and statistically

<sup>19</sup> The difference in coefficients from time taken is due almost entirely to the addition of subject fixed effects rather than task fixed effects.



*Notes:* This figure shows how the likelihood of a revision varies with the amount of time spent on the initial choice. The height of the bar gives the sample mean for each time window and the thinner lines give the 95% confidence interval for the mean. Decisions which were made very quickly were less likely to be revised, but outside of that range the time taken on a decision is negatively correlated with revision rates.

**Fig. 11** Revision Rates by Time Taken

**Table 5** Decision Time

	(1) Abs. Revision	(2) Abs. Revision	(3) Abs. Revision	(4) Abs. Revision
Seconds on Page	0.00031 (0.020)	-0.025 (0.023)	0.033*** (0.012)	0.0069 (0.013)
Round		-0.083*** (0.018)		-0.068*** (0.017)
Subject FE	No	No	Yes	Yes
Task FE	No	No	Yes	Yes
Observations	6516	6516	6516	6516

*Notes:* Linear regression clustered at the subject level. Each column represents a different regression, but all columns use the absolute value of the revision as the dependent variable. Significance indicated by: \*\*\*  $p < 0.01$ , \*\*  $p < 0.05$ , \*  $p < 0.1$ .

**Table 6** Budget Characteristics

	(1) Made Revision	(2) Abs. Revision	(3) Made Revision	(4) Abs. Revision
Max Prize	-0.00012 (0.00011)	-0.0024 (0.0039)	-0.00055*** (0.00019)	-0.014** (0.0062)
Max Probability	-0.095*** (0.025)	-2.33** (1.00)		
Subject FE	Yes	Yes	Yes	Yes
Price FE	No	No	Yes	Yes
Observations	6516	6516	6516	6516

*Notes:* Linear regression clustered at the subject level. Each column represents a different regression, with the column head specifying the dependent variable. Significance indicated by: \*\*\*  $p < 0.01$ , \*\*  $p < 0.05$ , \*  $p < 0.1$ .

insignificant. After controlling for individual fixed effects, the relationship between time taken and the size of revisions is driven by the fact that subjects both take longer and make more mistakes when they are less experienced.<sup>20</sup>

#### 6.4 Budget characteristics

In this subsection we consider whether budget characteristics affect the likelihood that decision makers revise their choices. Thus, Table 6 studies how the characteristics of the budgets relate to revisions.

Columns (1) and (2) of Table 6 show the linear relationship between the characteristics of budgets and the size and likelihood of making a revision.<sup>21</sup> The coefficient for both regressions on the maximum prize is near zero. Thus, the potential size of the prize does not affect the likelihood that the decision maker makes a mistake. This contrasts with the coefficient on the maximum likelihood of receiving the prize, which is significantly negative. This implies that subjects have a harder time making choices when the probabilities that they are choosing between are small.

Columns (3) and (4) of Table 6 include price fixed effects. Holding the relative price of prize and probability constant, the coefficient on Max Prize is the effect of pure increase in income (a parallel shift in the budget line). Thus, the negative coefficient on Max Prize shows that as income increases, both the likelihood of making a revision and the average size of revisions decrease.

<sup>20</sup> Table 2 of Online Appendix B completes the same analysis for a binary variable capturing whether a revision took place. The overall pattern of results is the same, with the exception of column (4). When making the revision is the dependent variable, the effects of neither time taken nor round are statistically significant (although they are jointly significant with  $p < 0.05$ ) and the coefficient on time taken is larger relative to the coefficient on round.

<sup>21</sup> Similar analysis is completed more flexibly (e.g., using Max Prize fixed effects when estimating the linear coefficient on Max Probability) in Table 1 of Online Appendix B. The results do not substantively change.

## 7 Conclusion

Do revisions reveal mistakes? We find that indeed revised choices improve welfare according to all our normative benchmarks. Revealed preference analysis suggests further that these revisions are closer to being generated by a strictly increasing utility function. Revised behavior is, therefore, more consistent with models that assume individuals have complete and transitive preferences over all alternatives. Thus, choices that are later revised are likely to be mistakes. Researchers can thus use revisions to identify mistakes in other settings because the approach does not depend on a particular choice environment and does not rely on the researcher's evaluation of the correct choice.

What lessons can we learn from detecting mistakes? One lesson is that mistakes are common, meaningful, and potentially make it more challenging to observe preferences. Fortunately, adherence to how we believe individuals *ought* to behave improves with a simple prompt to revise. Future applications may use this method to distinguish between biases (preferences) and heuristics (mistakes). For example, present bias may be driven by a preference for the immediate or an inability to plan over a long horizon. A second lesson is that mistakes are made when the outcomes are unlikely and when the environment is unfamiliar. Choosing from sets with these characteristics may be more difficult. A third lesson is that reminders make revisions less likely, highlighting a potential tradeoff between the desire for consistency and choosing what one prefers in the moment. Whether demand effects, status quo bias, or memory is behind this discrepancy remains an open question.

We conclude with three recommendations for future experimental work.

The first suggestion is to carefully consider whether the choices made by inexperienced subjects truly represent their preferences. The body of evidence that we collect suggests that many such choices are more likely to be made in error. One strategy to overcome this would be to focus any model estimation or statistical tests on the data without omitting these early choices—indeed, this strategy is already used in some existing research. The amount of experience that a subject needs before their choices can be expected to represent their preferences accurately is likely positively related to the complexity and unfamiliarity of the decision environment. For the environment shown in this paper, the quadratic specification we used in Table 4 showed that while the absolute size of revisions decreases until about the fortieth round, nearly 50% of the decrease occurs by round ten, and 75% of this occurs by round 20.

Our second recommendation is that researchers should directly analyze choices made with less experience and compare them to choices made with more experience. This will help to identify not only types of decision problems in which mistakes are made naively but also to identify the mistakes they make. This comparison can be made more cleanly if the experiment includes another feature of our design: repetitions of choice problems. Experimenters may find such repetitions wasteful if subjects do not make mistakes, but our results show that this is not the case. We also note, however, that if the researcher thinks that the preferences

for randomization identified in Agranov and Ortoleva (2017) and Agranov et al. (2023) are relevant for their subjects, it will be essential to use revisions rather than simple repetitions.

Our third recommendation is related to the first two. Allowing subjects to go back and forth through the experimental tasks may enable subjects to revise earlier decisions. Prompts to verify earlier choices may also nudge subjects towards revising their choices. Overall, we expect subjects to revise those choices about which they feel less sure. We also note that allowing this flexibility makes revisions endogenous, so this approach may make it harder to identify mistakes.

**Supplementary Information** The online version contains supplementary material available at <https://doi.org/10.1007/s11166-024-09429-3>. **Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

## References

- Afriat, S. N. (1967). The construction of utility functions from expenditure data. *International Economic Review*, 8(1), 67–77.
- Afriat, S. N. (1973). On a system of inequalities in demand analysis: an extension of the classical method. *International Economic Review*, 14(2), 460–472. <https://doi.org/10.2307/2525934>
- Agarwal, S., Ben-David, I., & Yao, V. (2017). Systematic mistakes in the mortgage market and lack of financial sophistication. *Journal of Financial Economics*, 123(1), 42–58.
- Agranov, M., Healy, P. J., & Nielsen, K. (2023). Stable randomisation. *The Economic Journal*, 133(655), 2553–2579.
- Agranov, M., & Ortoleva, P. (2017). Stochastic choice and preferences for randomization. *Journal of Political Economy*, 125(1), 40–68.
- Allcott, H., & Taubinsky, D. (2015). Evaluating behaviorally motivated policy: Experimental evidence from the lightbulb market. *American Economic Review*, 105(8), 2501–2538.
- Andreoni, J., & Harbaugh, W. (2009). *Unexpected utility: Five experimental tests of preferences for risk*. Working paper.
- Andreoni, J., & Miller, J. (2002). Giving according to garp: An experimental test of the consistency of preferences for altruism. *Econometrica*, 70(2), 737–753.
- Benjamin, D. J., Fontana, M. A., & Kimball, M. S. (2020). *Reconsidering risk aversion*. NBER Working Paper No. w28007.
- Benkert, J.-M., & Netzer, N. (2018). Informational requirements of nudging. *Journal of Political Economy*, 126(6), 2323–2355.
- Bernheim, B. D. (2016). The good, the bad, and the ugly: A unified approach to behavioral welfare economics. *Journal of Benefit-Cost Analysis*, 7(1), 12–68.
- Bernheim, B. D., Fradkin, A., & Popov, I. (2015). The welfare economics of default options in 401(k) plans. *American Economic Review*, 105(9), 2798–2837.
- Bernheim, B. D., & Rangel, A. (2009). Beyond revealed preference: Choice-theoretic foundations for behavioral welfare economics. *The Quarterly Journal of Economics*, 124(1), 51–104.
- Bernheim, B. D., & Taubinsky, D. (2018). Chapter 5 - Behavioral public economics. In B. D. Bernheim, S. DellaVigna, & D. Laibson (Eds.), *Handbook of Behavioral Economics: Applications and Foundations 1*, Volume 1, (pp. 381–516). North-Holland. <https://doi.org/10.1016/bs.hesbe.2018.07.002>.

- <https://www.sciencedirect.com/science/article/pii/S2352239918300022>. ISSN: 2352-2399, ISBN: 9780444633743.
- Bhargava, S., Loewenstein, G., & Sydnor, J. (2017). Choose to lose: Health plan choices from a menu with dominated option. *The Quarterly Journal of Economics*, 132(3), 1319–1372.
- Birnbaum, M. H., & Schmidt, U. (2015). The impact of learning by thought on violations of independence and coalescing. *Decision Analysis*, 12(3), 144–152.
- Bronars, S. G. (1987). The power of nonparametric tests of preference maximization. *Econometrica*, 55(3), 693–698.
- Camerer, C. F. (1989). An experimental test of several generalized utility theories. *Journal of Risk and Uncertainty*, 2(1), 61–104.
- Caplin, A., Dean, M., & Martin, D. (2011). Search and satisficing. *American Economic Review*, 101(7), 2899–2922.
- Chen, D. L., Schonger, M., & Wickens, C. (2016). oTree: An open-source platform for laboratory, online, and field experiments. *Journal of Behavioral and Experimental Finance*, 9(1), 88–97.
- Chetty, R., Looney, A., & Kroft, K. (2009). Salience and taxation: Theory and evidence. *American Economic Review*, 99(4), 1145–1177.
- Choi, J. J., Laibson, D., & Madrian, B. C. (2011). \$100 bills on the sidewalk: Suboptimal investment in 401 (k) plans. *Review of Economics and Statistics*, 93(3), 748–763.
- Choi, S., Fisman, R., Gale, D., & Kariv, S. (2007). Consistency and heterogeneity of individual behavior under uncertainty. *American Economic Review*, 97(5), 1921–1938.
- Choi, S., Kariv, S., Müller, W., & Silverman, D. (2014). Who is (more) rational? *American Economic Review*, 104(6), 1518–1550.
- Demuynck, T., & Rehbeck, J. (2023). Computing revealed preference goodness-of-fit measures with integer programming. *Economic Theory*, 76, 1175–1195. <https://doi.org/10.1007/s00199-023-01489-x>
- Feldman, P., & Rehbeck, J. (2022). Revealing a preference for mixtures: An experimental study of risk. *Quantitative Economics*, 13(2), 761–786.
- Fudenberg, D., & Levine, D. K. (2006). A dual-self model of impulse control. *American Economic Review*, 96(5), 1449–1476.
- Garcia-Retamero, R., & Hoffrage, U. (2013). Visual representation of statistical information improves diagnostic inferences in doctors and their patients. *Social Science & Medicine*, 83, 27–33.
- Gathergood, J., Mahoney, N., Stewart, N., & Weber, J. (2019). How do individuals repay their debt? The balance-matching heuristic. *American Economic Review*, 109(3), 844–875.
- Gaudeul, A., & Crosetto, P. (2019). *Fast then slow: A choice process explanation for the attraction effect*. Working paper.
- Goldin, J., & Reck, D. (2020). Revealed-preference analysis with framing effects. *Journal of Political Economy*, 128(7), 2759–2795.
- Halevy, Y., Persitz, D., & Zrill, L. (2018). Parametric recoverability of preferences. *Journal of Political Economy*, 126(4), 1558–1593.
- Hey, J. D. (2001). Does repetition improve consistency? *Experimental Economics*, 4(1), 5–54.
- Hey, J. D., & Orme, C. (1994). Investigating generalizations of expected utility theory using experimental data. *Econometrica*, 62(6), 1291–1326. <https://doi.org/10.2307/2951750>
- Hoffrage, U., Lindsey, S., Hertwig, R., & Gigerenzer, G. (2000). Communicating statistical information. *Science*, 290(5500), 2261–2262.
- Hong, C. S., Karni, E., & Safra, Z. (1987). Risk aversion in the theory of expected utility with rank dependent probabilities. *Journal of Economic Theory*, 42(2), 370–381.
- Houtman, M., & Maks, J. (1985). Determining all maximal data subsets consistent with revealed preference. *Kwantitatieve Methoden*, 19(1), 89–104.
- Jacobson, S., & Petrie, R. (2009). Learning from mistakes: What do inconsistent choices over risk tell us? *Journal of Risk and Uncertainty*, 38(2), 143–158.
- Kalayci, K., & Serra-Garcia, M. (2016). Complexity and biases. *Experimental Economics*, 19(1), 31–50.
- Khaw, M. W., Li, Z., & Woodford, M. (2021). Cognitive imprecision and small-stakes risk aversion. *The Review of Economic Studies*, 88(4), 1979–2013.
- Kneeland, T. (2015). Identifying higher-order rationality. *Econometrica*, 83(5), 2065–2079.
- Koszegi, B., & Rabin, M. (2008). Revealed mistakes and revealed preferences. In A. Caplin & A. Schotter (Eds.), *The Foundations of Positive and Normative Economics: A Handbook* (pp. 193–209). Oxford University Press.
- Martínez-Marquina, A., Niederle, M., & Vespa, E. (2019). Failures in contingent reasoning: The role of uncertainty. *American Economic Review*, 109(10), 3437–3474.

- Nielsen, K., & Rehbeck, J. (2022). When choices are mistakes. *American Economic Review*, 112(7), 2237–2268.
- Nishimura, H., Ok, E. A., & Quah, J. K.-H. (2017). A comprehensive approach to revealed preference theory. *American Economic Review*, 107(4), 1239–1263.
- Polisson, M., Quah, J. K.-H., & Renou, L. (2020). Revealed preferences over risk and uncertainty. *American Economic Review*, 110(6), 1782–1820.
- Ponce, A., Seira, E., & Zamarripa, G. (2017). Borrowing on the wrong credit card? Evidence from Mexico. *American Economic Review*, 107(4), 1335–1361.
- Quiggin, J. (1982). A theory of anticipated utility. *Journal of Economic Behavior & Organization*, 3(4), 323–343.
- Ratcliff, R. (1978). A theory of memory retrieval. *Psychological Review*, 85(2), 59–108. <https://doi.org/10.1037/0033-295X.85.2.59>
- Ratcliff, R., & McKoon, G. (2008). The diffusion decision model: Theory and data for two-choice decision tasks. *Neural Computation*, 20(4), 873–922.
- Tversky, A. (1969). Intransitivity of preferences. *Psychological Review*, 76(1), 31–48. <https://doi.org/10.1037/h0026750>
- Varian, H. R. (1982). The nonparametric approach to demand analysis. *Econometrica*, 50(4), 945–973. <https://doi.org/10.2307/1912771>
- Yaari, M. E. (1987). The dual theory of choice under risk. *Econometrica*, 55(1), 95–115. <https://doi.org/10.2307/1911158>
- Yu, C. W., Zhang, Y. J., & Zuo, S. X. (2021). Multiple switching and data quality in the multiple price list. *Review of Economics and Statistics*, 103(1), 136–150.

**Publisher's Note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.