American Economic Journal: Microeconomics 3 (November 2011): 35–67
http://www.aeaweb.org/articles.php?doi=10.1257/mic.3.4.35

Mnemonomics: The Sunk Cost Fallacy as a Memory Kludge†

By Sandeep Baliga and Jeffrey C. Ely*

We offer a theory of the sunk cost fallacy as an optimal response to limited memory. As new information arrives, a decision-maker may not remember all the reasons he began a project. The sunk cost gives additional information about future profits and informs subsequent decisions. The Concorde effect makes the investor more eager to complete projects when sunk costs are high and the pro-rata effect makes the investor less eager. In a controlled experiment we had subjects play a simple version of the model. In a baseline treatment subjects exhibit the pro-rata bias. When we induce memory constraints the effect reverses and the subjects exhibit the Concorde bias. (*JEL* D24, D83, G31)

In this paper we present a new theory of the origin of sunk-cost biases and report the results of a novel experiment which lends some support to the theory.

Rational agents unhindered by limits on information processing should not take sunk costs into account when evaluating current decisions. But experimental and anecdotal evidence suggests that this normative principle is not employed by real-world decision-makers. The evidence for this *sunk cost fallacy* comes in two forms.

In a classic experiment, Hal R. Arkes and Catherine Blumer (1985) sold theater season tickets at three randomly selected prices. Those who purchased at the two discounted prices attended fewer events than those who paid the full price. Hal Arkes and Peter Ayton (1999) suggest those who had "sunk" the most money into the season tickets were most motivated to use them. R. Dawkins and T. R. Carlisle (1976) call this behavior the *Concorde effect.* France and Britain continued to invest in the Concorde supersonic jet after it was known it was going to be unprofitable. This so-called "escalation of commitment" results in an over-investment in an activity or project.

Sunk and fixed costs can also have the opposite effect. For example, Howard Garland, Craig A. Sandefur, and Anne C. Rogers (1990) conducted a survey of petroleum geologists. The subjects were asked whether to continue a petroleum-exploration

* Baliga: Kellogg Graduate School of Management, Northwestern University, 2001 Sheridan Road, Evanston, IL 60208 (e-mail: baliga@kellogg.northwestern.edu); Ely: Department of Economics, Northwestern University, 2001 Sheridan Road, Evanston, IL 60208 (e-mail: jeffely@northwestern.edu). We thank the Zell Center for Risk Research for financial assistance. We thank Sven Feldman, Ariel Rubinstein, and seminar audiences at NYU, MIT, Columbia, and Boston University. Two anonymous referees gave valuable suggestions which improved the paper. John Norstad did a wonderful job programming the software for the experiment and Ija Trapeznikova and Mark Chicu provided indispensable research assistance. We thank Dan Garrett for proofreading. As for the errors that remain, someone is to blame but we forget who.

† To comment on this article in the online discussion forum, or to view additional materials, visit the article page at http://www.aeaweb.org/articles.php?doi=10.1257/mic.3.4.35.

project when one to four dry wells had been drilled. The greater the number of dry wells drilled and the higher the sunk cost, the less likely were the geologists to support continuing the project. In surveys of pricing practices of US companies, Vijay Govindarajan and Robert Anthony (1995), Eunsup Shim (1993), and Shim and Ephraim F. Sudit (1995) find that most firms price their products based on "full costing" methodologies that pro-rata some element of fixed and sunk costs into variable costs. Indeed, John K. Shank and Govindarajan (1989) put full cost pricing on an equal footing with the prescriptions of economic theory: "Business history reveals as many sins by taking an incremental view as by taking the full cost view" (see Nabil Al-Najjar, Sandeeb Baliga, and David Besanko 2008 for other references). Full-cost pricing results in prices that are too high so sales are low. In this case, the decision-maker does not want "to throw good money after bad" and the sunk cost fallacy manifests itself as an underinvestment in production. We call this type of behavior the *pro-rata fallacy*. As far as we know, this version of the sunk cost fallacy has not been documented as thoroughly as the Concorde effect.

We provide a theory of sunk cost bias as a substitute for limited memory. We consider a model in which a project requires two stages of investment to complete. As new information arrives, a decision-maker or investor may not remember his initial forecast of the project's value. The sunk cost of past actions conveys information about the investor's initial valuation of the project and is therefore an additional source information when direct memory is imperfect. This means that a rational investor with imperfect memory should incorporate sunk costs into future decisions.

We show that in different environments, this logic can generate the Concorde and pro-rata fallacies. If the investor has imperfect memory of his profit forecast, a high sunk cost signals that the forecast was optimistic enough to justify incurring the high cost. For example, the willingness to incur a high sunk cost digging dry wells may signal that the oil exploration project is worth continuing. If this is the main issue the investor faces, it generates the Concorde effect as he is more likely to continue a project which was initiated at a high cost. On the other hand, if current costs are positively correlated with future costs, a high sunk cost signals lower profits, other things equal. This environment generates the pro-rata effect, as the investor is more likely to cancel projects with a high sunk cost. A high cost of digging wells may signal high costs of extraction later on. There are then two opposing effects and their relative magnitude determines whether the Concorde or pro-rata bias is observed.

There are a few different ways these effects can manifest themselves in practice. Most directly, the decision maker may be an individual responsible for making the initiation and continuation decision and he may simply forget the information.[1] An organization may also forget information or knowledge.[2] Managerial turnover can

[1] Charles D. Bailey (1989) conducted an experiment which simulated a production interruption. Subjects first took part in the experimental task and then returned later to perform the same task. Bailey (1989) found significant rates of forgetting at the individual level.

[2] For example, a firm's stock of production experience may depreciate over time so its costs of production do not decline rapidly and may even rise. This form of "organizational forgetting" has been found in empirical studies of aircraft manufacture (Linda Argote, Sara L. Beckman, and Dennis Epple 1990; Lanier Benkard 2000), shipbuilding (Argote, Beckman, and Epple 1990) and pizza franchises (Argote, Eric Darr, and Epple 1995).

generate organizational forgetting.[3] In this case, we can think of the investor in the model as representing a long-lived organization headed by a sequence of short-term executives. An executive who inherits an ongoing project will not have access to all of the information available at the time of planning. Existing strategies and plans will then encode missing information and a new executive may continue to implement the plans of the old executive.[4] In our model, data about sunk costs partially substitutes for missing information and a rational executive takes this into account.

Finally, we can think of sunk-cost bias as a kludge: an adaptive heuristic wherein metaphorical Nature is balancing a design tradeoff.[5] There is a rich and interesting literature in this tradition originating with Arthur J. Robson (2001). Robson (2001) lays out a formal framework for studying preferences as Nature's mechanism for inducing adaptive behavior. In Larry Samuelson and Jeroen M. Swinkels (2006), Luis Rayo and Gary Becker (2007), Robson and Samuelson (forthcoming), this framework is used to consider how preferences shape behavior to work around physical constraints. In our model, the sunk cost bias is an optimal heuristic that compensates for the constraints of limited memory. This can explain the prevalence and persistence of sunk-cost bias despite its appearance, superficially, as a fallacy. To the extent that heuristics are hard-wired or built into preferences, the sunk-cost bias in observed behavior would be adapted to the "average" environment but not always a good fit in specific situations. For example, we would expect that decision-makers display a sunk-cost bias even when full memory is available, and that sometimes the bias goes in the wrong direction for the specific problem at hand.

We conducted an experiment to study whether the Concorde and pro-rata fallacies exist and how they operate. Participants in the experiment faced a sequential investment problem. They were told the profits from a completed project and a cost of initiation. Later on, they were told a cost of completion. There was no correlation between costs of initiation and completion. In the control version of the problem, the participants have full information at all stages of investment. In the limited-memory treatment, subjects had to rely on their memory of the profit at the stage in which they decide whether to complete the project.

Our main findings are as follows. In the baseline setting, where the participants have all the relevant information to make an optimal completion decision, we find strong evidence for the presence of the pro-rata bias: subjects are inclined to add

[3] For example, Vikas Anand, Charles C. Manz, and William Glick (1998) report: "Managers at the propulsion systems division of a major aerospace company selected an engineer to become the in-house expert in a new technology. In a wave of management changes, the champions of the technology all moved out of the division. The expert engineer was reassigned to normal duties. After another wave of changes in management, it became apparent that the technology was critical, but no one remembered that there was an expert already on staff, and the process was repeated."

[4] For example, when John Akers stepped down and Lou Gerstner became C.E.O. of IBM in 1993, he was determined to "carry out a set of policies put in place by none other than the much-maligned Akers." He was not "rushing to make significant changes in vision" but was "still following through on Akers' two-year-old restructuring." He believed that "IBM has yet to test fully many if the changes Akers put in place" and said, "I want to make sure the current system is implemented before we try any alternatives." We interpret Gerstner's decision-making as follows: Akers' old plans were initiated using information known to him at the time. By the time Gerstner arrived, the direct information was lost but was manifested indirectly in the strategic plan he inherited. Hence, this generated a bias to implement the old plan.

[5] This view is not without its critics. See S. J. Gould and R. C. Lewontin (1979).

the costs of initiation to the costs of completion rather than subtract them or ignore them altogether. This result is of independent interest because it is evidently the first laboratory experiment of a sequential investment problem and well-known field experiments such as Arkes and Blumer (1985) point to the Concorde bias. As we discuss below, field experiments are prone to selection bias which may produce what appears to be a Concorde bias even if subjects are unbiased.

The baseline pro-rata fallacy is consistent with the interpretation of biases as heuristics but not with a direct application of our theory. If past experience has taught subjects that a large sunk cost usually signals a cost overrun, they are inclined to cancel projects early even if this is inappropriate for the current problem. Of course, there might be some other explanation for why subjects make errors. Such an explanation would have to identify why subjects make errors in the direction of the pro-rata fallacy and not the reverse.

In the limited-memory treatment of our experiment, we find evidence of the Concorde effect. First, when we study the entire sample, the baseline pro-rata tendency is reversed, and the subjects exhibit the Concorde effect. The magnitude of this reversal is large and highly significant. Second, when we study the subsample of subjects who never commit the pro-rata fallacy in the full memory treatment, the Concorde effect is again large and significant. On average, subjects are roughly 20–30 percent more likely to complete the project when the initiation cost is large than when it is small.

These findings lend partial support for the theory but also present some challenges. For instance, if a decision-maker is subject to more than one behavioral bias, what determines which bias operates at the point where he makes a choice? In Section III we offer one possible unifying explanation based on the idea of "fast and frugal" heuristics proposed by Gerd Gigerenzer and Daniel G. Goldstein (1996).

Other Related Literature.—Economists and psychologists have offered many explanations of sunk-costs biases and elicited the biases in experiments. A pro-rata bias may facilitate implicit collusion in a Bertrand oligopoly. For example, being known to have a pro-rata bias may facilitate collusion by oligopolists who incur sunk costs. In support of this, Theo Oerman and Jan Potters (2006) experimentally identify some degree of full-cost pricing by competitive firms who have incurred sunk entry costs. On the other hand, they find that pricing by a monopolist is not affected by sunk costs, suggesting that the source of the bias was purely strategic.

There are surprisingly few laboratory studies of sunk cost bias involving monetary payoffs and none as simple as the two-stage binary investment decision we study here. Owen R. Phillips, Raymond C. Battalio, and Carl A. Kogut (1991) induced subjects to reveal their subjective value of various lottery tickets which differed only in terms of their price, a sunk cost. They conclude that when the sunk nature of the cost was made transparent to the subjects, the sunk cost effect almost disappears. In Chip Heath (1995) subjects were sold bets that paid a reward with a given probability and were allowed to buy into the bet repeatedly until the first time it paid off. Subjects often stopped buying into a bet once their (sunk) losses reached the amount of the reward. Daniel Friedman et al. (2007) presents a survey of the literature in economics and psychology and notes the elusiveness of convincing evidence for sunk cost bias. They also report the results of a laboratory study of their own, with mostly inconclusive results.

On the theory side, R. Preston McAfee, Hugo M. Mialon, and Sue H. Mialon (2010) and Chandra Kanodia, Robert Bushman, and John Dickhaut (1989) present models in which an agent loses reputation if he reverses course on an initial investment. This strategic incentive creates a Concorde effect. McAfee, Mialon, and Mialon (2010) also present a model of individual decision-making in which rational behavior gives rise to a Concorde effect. In this model when a high initial investment turns out to be insufficient to complete the project, this conveys information that the incremental costs are low due to a hazard rate assumption about completion probabilities. Erik Eyster (2002) shows that the Concorde bias can arise if decision-makers have a taste for rationalizing past decisions. None of these models would apply to our setting where we demonstrate theoretically and experimentally both pro-rata and Concorde biases.

Limited memory has been studied as a source of other biases in decision-making. For example, Andrea Wilson (2003) has studied a model where an agent with bounded memory observes a sequence of noisy signals. She shows that the decision-maker displays confirmatory bias and over/under-confidence in her ability to interpret ambiguous information. In a series of papers, Roland Benabou and Jean Tirole (2004, 2006) have studied the interaction between imperfect recall and psychological and sociological phenomena. Suppose, similar to our model, that agents do not remember their motivation but do remember their actions. Roland Benabou and Jean Tirole (2004) show that a decision-maker may commit to personal rules that deal with dynamic inconsistency, though at the cost of potential over-commitment. Similarly, an agent may engage in prosocial behavior to signal to future selves that he is a generous type (Benabou and Tirole 2006). Glenn Ellison and Drew Fudenberg (1993) show how agents who experiment with new technologies can use a form of popularity weighting as a substitute for imperfect memory of past outcomes. Finally, David Hirshleifer and Ivo Welch (2002) study a herding model where a forgetful individual remembers past actions but not past signals. The individual faces the same decision problem at each point in time and exhibits inertia. For a sunk cost fallacy to be generated, it is important that the cost structure change so an individual faces a different decision problem at different times.

Overview.—The rest of this paper is organized as follows. The following section lays out our theoretical model of sequential investment under imperfect memory. In Section IA, we analyze the benchmark solution under perfect memory and we give a formal denition of sunk-cost bias. We argue that this denition is empirically testable in the laboratory but that eld experiments are prone to selection bias. In Section IB and Section II, we show that the optimal response to limited memory generates a sunk-cost bias. These two sections decompose the bias into the Concorde and pro-rata eects identifying the sources of each. Along the way, Section IC and Section ID discuss some variations of the model. Section IIA presents a numerical example in which the pro-rata bias dominates for small projects and the Concorde bias dominates for large projects. The experiment is described in Section III and Section IV presents some concluding remarks.

I. Model

A risk-neutral investor is presented with a project which requires two stages of investment to complete. In the first stage, the investor obtains an estimate X of the expected value of the project and learns the cost c_1 required to initiate the project. If the investor decides to initiate, he incurs the cost c_1 and the project proceeds to the second stage. If the investor chooses not to initiate, the project is discarded and the investor's payoff is zero.

In the second stage the investor learns the cost c_2 required to complete the project. If the project is completed, the investor realizes the reward X resulting in a total payoff of $X - c_1 - c_2$. If instead the investor chooses not to complete the project, his total payoff is $-c_1$. Thus, the initiation cost is sunk in the second stage.

We will assume that X, c_1, and c_2 are all non-negative random variables and that $-X$ and c_1 are affiliated. We let $g(\cdot \,|\, c_1)$ be the strictly positive conditional density of X conditional on an initiation cost of c_1. By affiliation, if $c_1 > c_1'$ then $g(\cdot \,|\, c_1')$ is weakly greater than $g(\cdot \,|\, c_1)$ in the sense of the monotone likelihood ratio property (MLRP). Note that independence of c_1 and X is a special case of affiliation as we allow the density $g(\cdot \,|\, c_1)$ to be independent of c_1. We assume that c_2 is independent of all other variables. Let f be the density and F the c.d.f. of c_2.

The following primitive model generates these features. The project, once completed, will generate long run profit Λ equal to revenue R minus costs C. In the first stage, the investor observes a signal σ which conveys information about R. The short-run initiation cost c_1 and the long-run cost C are affiliated random variables and independent of R and σ. Upon observing both σ and c_1, the investor forms his expectation of Λ and this expectation is denoted X. That is,

$$\mathbf{E}(\Lambda \,|\, \sigma, c_1) \;=\; \mathbf{E}(R \,|\, \sigma) \;-\; \mathbf{E}(C \,|\, c_1) \;\equiv\; X.$$

With this structure, X is a sufficient statistic for the investor's decision making and the random variables c_1 and $-X$ are affiliated. We can thus abstract away from these details and adopt the reduced-form model described above.

A key ingredient in our model is that the investor may remember the sunk cost c_1 but forget the project's value X. There are many reasons why sunk costs may be remembered while ex ante payoffs may not. As in Benabou and Tirole (2004), while the decision-maker may forget his motivations, it may be easier to remember his actions and these actions generate sunk costs.

Consider the following concrete examples. A developer begins construction of an apartment complex after collecting information from a variety of sources about the local housing market, maintenance costs, and the value of alternative investments. A year later, when threatened by cost overruns, he has accumulated documentary evidence of expenses incurred but many of the details about project returns are pure memories. A PhD student has no written record of his original motives for attending grad school, but at the time of deciding whether to stick it out for another year he has a clear and salient measure of the sunk cost: the five years of his life he has been at it so far.

In Section ID, we study a variation of the model in which both c_1 and X are subject to memory lapses, and we show that similar results obtain. More generally, when the decision to initiate a project depends on both X and c_1, even the noisiest memory of c_1 will be useful information about X provided X is not remembered perfectly.

A. *Full Memory Benchmark*

In the benchmark model, the investor recalls in stage two the value of X. The optimal strategy for the investor is to complete any project for which $c_2 \leq X$ and to initiate projects for which the total expected costs $c_1 + \mathbf{E}(c_2 | c_2 \leq X)$ are less than $X \cdot F(X)$. The latter is the value of the project multiplied by the probability it will be completed if initiated. In particular, the second-stage investment decision is not influenced by c_1. If we were to collect data generated by such a decision-maker, the cost c_1 would not be predictive of the probability of completion *after controlling for X*. We are led to the following definition.[6]

DEFINITION 1: *The investor displays a* sunk cost bias *if, conditional on initiating a project with expected value X, the probability that he completes a project with an initiation cost* c_1 *differs from the probability he completes it for initiation cost* $c_1' \neq c_1$. *If this probability increases with* c_1 *then the investor exhibits the* Concorde *bias. If it decreases with* c_1 *then the investor exhibits the* pro-rata *bias.*

On the other hand, if we had anything less than a perfect measure of X in the data, then there would be spurious correlation between c_1 and the decision to complete. This would make even a fully rational investor appear to exhibit a Concorde effect.

B. *Independence and the Concorde Effect*

Now we turn to the model in which the investor forgets the value of X (but remembers c_1) in stage two. We begin with the special case of *independence:* c_1 and X are independently distributed. In Section ID we consider the case where the investor may forget either (or both) X and c_1. In Section II we relax the assumption of independence.

The investor's strategy now consists of the set of projects (X, c_1) he will initiate and, for each realization of the completion cost c_2, a decision whether to complete the project given his memory of c_1. For the moment, let us represent the investor's strategy by *thresholds*: $\overline{X}(c_1)$, $\overline{c}_2(c_1)$. When playing a threshold strategy, the investor initiates all projects (X, c_1) such that $X \geq \overline{X}(c_1)$ and, given memory c_1, completes all projects with completion costs $c_2 \leq \overline{c}_2(c_1)$.

The expected payoff to a threshold strategy can be expressed as follows. First, for any fixed c_1 and thresholds $\overline{X}$ and $\overline{c}_2$, the expected payoff conditional on c_1 is

$$(1) \qquad \Pi(\overline{X}, \overline{c}_2 | c_1) = \int_{\overline{X}}^{\infty} \left[\int_0^{\overline{c}_2} (X - c_2) f(c_2) \, dc_2 \right] - c_1 g(X) \, dX$$

[6] In all versions of our model, c_1 is independent of c_2. Since the completion probability is equal to the probability of the set of c_2 values at which the investor completes, this probability is independent of c_1. In a richer model in which c_1 and c_2 may be correlated, a careful definition of sunk-cost bias would have to control for the exogenous relationship between c_1 and any fixed set of completion costs c_2.

and the overall expected payoff to the strategy $\left(\overline{X}(c_1), \overline{c}_2(c_1)\right)$ (thresholds varying with c_1) is

$$\Pi\left(\overline{X}(\cdot), \overline{c}_2(\cdot)\right) = \mathbf{E}_{c_1}\Pi\left(\overline{X}(c_1), \overline{c}_2(c_1) \,|\, c_1\right).$$

We will characterize the optimal strategy for the investor, i.e. the strategy that maximizes Π. In particular, we will show that the optimal strategy is indeed a threshold strategy.

First, the decision problem we are studying is one of *imperfect recall* in the game-theoretic sense. It is known that the optimal strategies in such problems may not be time-consistent. That is, during the play of an optimal strategy, at some information set in the tree, the agent's Bayesian posterior may induce him to strictly increase his expected continuation payoff by deviating from what the strategy prescribes (see Michele Piccione and Ariel Rubinstein 1997). When this is the case, it would arguably be more convincing to analyze the decision problem as if it were a game played by multiple selves (here, the first-stage self and the second-stage self) and look for sequential equilibria.

We can show however that for this game, the strategy that maximizes Π is in fact a sequential equilibrium, and there is no time-consistency problem of the sort discussed above. This result will also be useful as it allows us to treat the problem interchangeably as a game and as an optimization problem according to convenience. In particular, it will imply immediately that the optimal strategy takes the threshold form.

The following proposition is proved in the Appendix. There is a simple intuition. At any strategy profile, a deviation at an information set in either the first stage or the second stage which raises the continuation payoff must also raise the overall payoff. Thus, there can be no such deviation from the optimal strategy.[7] The result does not use independence so it also applies to the general model in Section II.

PROPOSITION 1: *An optimal strategy is a sequential equilibrium outcome of the game played between the first-stage and second-stage investor.*

We will use this result to build intuition about the optimal strategy. In particular, the optimal strategy maximizes Π among potentially many sequential equilibria. We can obtain necessary conditions of the optimal strategy by considering necessary conditions for a sequential equilibrium.

With this view, the memory of c_1 conveys information about the forgotten X and thus the investor optimally reacts to this information. (This response will give rise to the sunk-cost bias.) The optimal strategy for the investor in stage two is to complete a project if and only if the completion cost c_2 is less than the expected value of the project conditional on knowing that the project was initiated at a cost c_1. Clearly this cutoff depends on the initiation strategy in the first stage which in turn depends on what the investor anticipates in the first stage to be his second stage

[7] This distinguishes the game from games such as The Absent-Minded Driver Game (Piccione and Rubinstein 1997), where a deviation that raises continuation payoff can lower the ex-ante payoff.

completion strategy. In a sequential equilibrium we solve for these two strategies simultaneously.

We can show that the optimal strategy uses thresholds. At the second stage, when the investor recalls that initiation cost was c_1, the optimal completion strategy does not depend on the initiation strategy at some different cost c_1'. This implies that the first stage initiation strategy also depends only the realized initiation cost. Hence, we analyze the initiation and completion strategies for each initiation cost separately. Let $X(c_1)$ be the set of expected values for which the investor initiates the project when his initiation cost is c_1. At the second stage, the initiation cost is sunk and the investor completes the project if and only if the cost of completion is less than the expected value of the project:

$$c_2 \leq \mathbf{E}(X | X \in X(c_1)) \equiv \overline{c}_2(c_1).$$

That is, the optimal completion strategy is a threshold strategy where the investor completes the project if and only if $c_2 \leq \overline{c}_2(c_1)$. If $X \in X(c_1)$ and the investor initiates the project, we must have

$$\int_0^{\overline{c}_2(c_1)} (X - c_2) f(c_2) dc_2 - c_1 \geq 0. \tag{2}$$

If $X' > X$, as long as the completion strategy does not change, the investor should also initiate the project when the expected value is X' and the cost of initiation is c_1. But since X' will be forgotten, the completion strategy does not change if the investor initiates the project at X'. This implies that $X' \in X(c_1)$ and the optimal initiation strategy is also a threshold strategy. The threshold is the value of X which satisfies the inequality in equation (2) with equality.

To summarize, a necessary condition for the pair $\left(\overline{X}(c_1), \overline{c}_2(c_1)\right)$ to maximize profits is that the two strategies satisfy the following "reaction" equations.

$$\int_0^{\overline{c}_2(c_1)} (\overline{X}(c_1) - c_2) f(c_2) dc_2 - c_1 = 0 \tag{3}$$

$$\mathbf{E}(X | X \geq \overline{X}(c_1)) - \overline{c}_2(c_1) = 0. \tag{4}$$

The first equation implies that the investor is indifferent between initiating and discarding a project with expected value $\overline{X}(c_1)$, given the second-stage strategy $\overline{c}_2(c_1)$. The second equation implies that the investor is indifferent between completing and abandoning a project whose completion cost is $\overline{c}_2(c_1)$ given the first-stage strategy $\overline{X}(c_1)$. Due to the monotonicity of the profits in X and c_2, these conditions are equivalent to the two threshold strategies being best responses to one another. Note that these equations therefore characterize all sequential equilibria. They are thus necessary, but not sufficient conditions for the optimal profile.

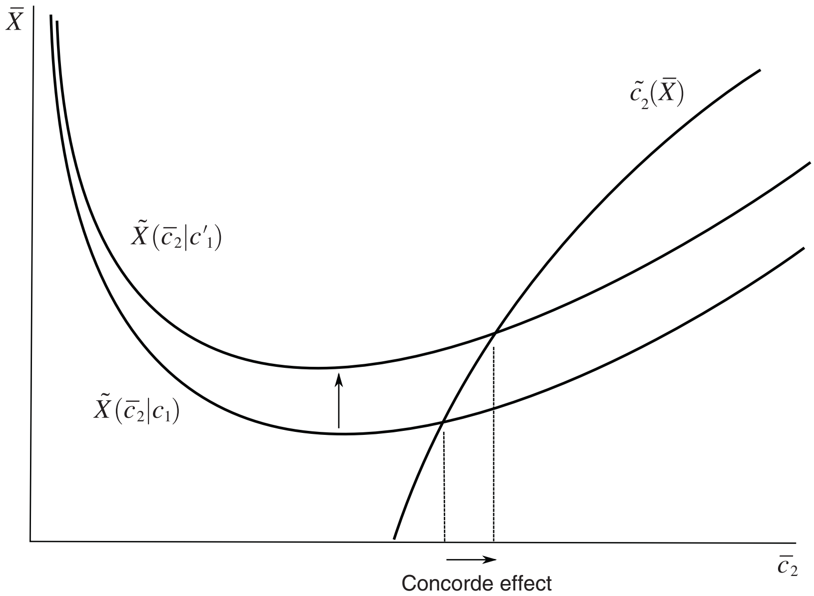


Figure 1. The Concorde Effect

To analyze these conditions, it is convenient to examine the following "reaction functions":

$$\tilde{X}(\overline{c}_2\,|\,c_1) \;=\; \frac{c_1}{F(\overline{c}_2)} \;+\; \mathbf{E}(c_2\,|\,c_2 \;\leq\; \overline{c}_2) \tag{5}$$

$$\tilde{c}_2(\overline{X}) \;=\; \mathbf{E}(X\,|\,X \;\geq\; \overline{X}). \tag{6}$$

For a given value of c_1, the reaction function $\tilde{X}(\overline{c}_2\,|\,c_1)$ gives the initiation threshold which is a best response to a given completion threshold $\overline{c}_2$. Likewise, the reaction function $\tilde{c}_2(\overline{X})$ gives the completion threshold which is a best response to a given initiation threshold $\overline{X}$. Note that the optimal threshold function $\tilde{c}_2\big(\overline{X}\big)$ does not depend on c_1. (This is due to the special case of independence which will be relaxed next.) For each c_1, the intersection of these reaction functions determine the thresholds $\overline{X}(c_1)$ and $\overline{c}_2(c_1)$. We then analyze how the intersection point responds to changes in c_1.

Figure 1 illustrates. The reaction function $\tilde{X}(\overline{c}_2|c_1)$ first slopes downward and then slopes upward: when $\overline{c}_2$ is low, the first term in equation (5) dominates and is decreasing in $\overline{c}_2$; when $\overline{c}_2$ is high, the second term in equation (5) dominates and is increasing in $\overline{c}_2$. The reaction curve $\tilde{c}_2(\overline{X})$ is *strictly* increasing as the density of the reward X is strictly positive. The figure represents the analytically simplest case in which there is a single point of intersection. As the function $\tilde{c}_2(\overline{X})$ does not depend on c_1, the only effect of an increase in c_1 is an upward shift in the curve $\tilde{X}(\overline{c}_2|c_1)$. Therefore, the intersection point moves along the $\tilde{c}_2(\overline{X})$ curve. The result is that the equilibrium threshold $\overline{c}_2(c_1)$ moves to the right. This is the Concorde effect: an

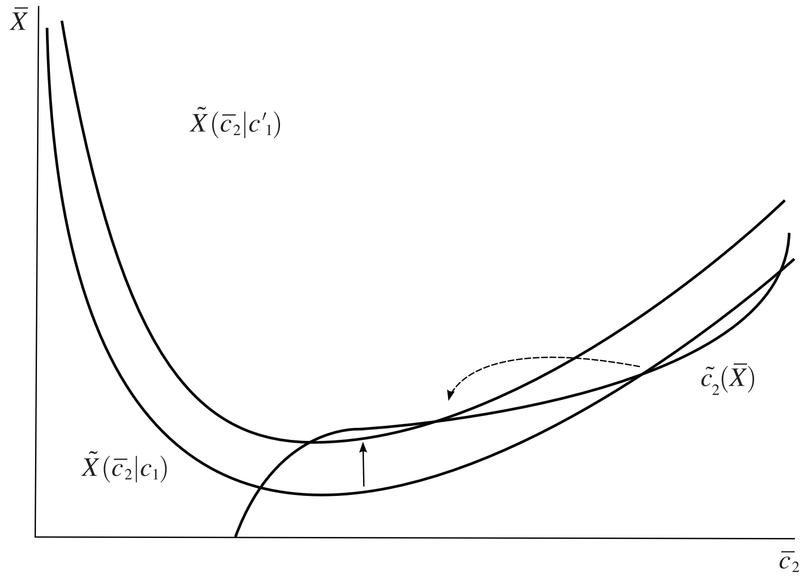


FIGURE 2. ISSUES IN DEMONSTRATING THE CONCORDE EFFECT

increase in the sunk cost increases the probability that the project will be completed.

There is a simple intuition for the Concorde effect. Other things equal, a larger initiation cost makes the investor more selective: he initiates projects with higher profits on average. Knowing this, a higher initiation cost makes the investor willing to complete projects with higher completion costs. However, this intuition does not immediately translate into a proof. In general there will be multiple intersection points and so a complete analysis requires us to analyze how the optimal profile selects among these intersection points and how that selection is affected by changes in c_1.

The potential difficulties are illustrated in Figure 2. At points where the $\tilde{c}_2$ reaction curve crosses from above, the upward shift in the $\tilde{X}$ reaction curve causes $\tilde{c}_2$ to go down. In addition, some intersection points may disappear altogether, potentially causing a jump downward to the remaining intersection point.

Nevertheless, we are able to demonstrate the Concorde bias in the following proposition. The proof applies a revealed preference argument to show that any shift among intersection points must be an upward shift.

PROPOSITION 2: *When X and c_1 are independent, a larger sunk cost leads to a greater probability of completion even after conditioning on X.*

PROOF:

Let $(\overline{X}^*, \overline{c}_2^*)$ be a profile which maximizes $\Pi(\overline{X}, \overline{c}_2 \,|\, c_1)$ and let $(\overline{X}, \overline{c}_2)$ be any profile for which $\overline{X} < \overline{X}^*$. Consider a larger initiation cost $c_1' > c_1$. We can re-write the conditional expected profit formula in equation (1) as follows

$$\Pi(\overline{X}, \overline{c}_2 \,|\, c_1) = \int_{\overline{X}}^{\infty} \int_0^{\overline{c}_2} (X - c_2) f(c_2) g(X)\, dc_2\, dX - \big(1 - G(\overline{X})\big) c_1.$$

Thus,

$$\Pi(\overline{X}^*, \overline{c}_2^* | c_1') = \Pi(\overline{X}^*, \overline{c}_2^* | c_1) - (1 - G(\overline{X}^*))(c_1' - c_1) \tag{7}$$

and

$$\Pi(\overline{X}, \overline{c}_2 | c_1') = \Pi(\overline{X}, \overline{c}_2 | c_1) - (1 - G(\overline{X}))(c_1' - c_1).$$

Because $\Pi(\overline{X}^*, \overline{c}_2^* | c_1) \geq \Pi(\overline{X}, \overline{c}_2 | c_1)$ and $(1 - G(\overline{X}^*)) < (1 - G(\overline{X}))$, we have

$$\Pi(\overline{X}^*, \overline{c}_2^* | c_1') > \Pi(\overline{X}, \overline{c}_2 | c_1')$$

so that $(\overline{X}, \overline{c}_2)$ cannot be a profit-maximizing profile when the initiation cost is c_1'. We have shown that the profit maximizing first stage threshold $\overline{X}$ cannot decrease as a result of an increase in the initiation cost. Because any profit maximizing profile $(\overline{X}, \overline{c}_2)$, must satisfy the reaction equation (equation (6))

$$\overline{c}_2 = \tilde{c}_2(\overline{X}) = \mathbf{E}(X | X \geq \overline{X}).$$

It follows that the profit-maximizing $\overline{c}_2$ must weakly increase in response to an increase in c_1. We now show that it must increase strictly. Assume instead that $\overline{c}_2$ remains constant. Because the $\tilde{c}_2(\overline{X})$ reaction curve is strictly increasing, $\overline{X}$ must remain constant as well. But the same pair $(\overline{X}, \overline{c}_2)$ cannot satisfy the other reaction equation (equation (5))

$$\overline{X} = \tilde{X}(\overline{c}_2 | c_1) = \frac{c_1}{F(\overline{c}_2)} + \mathbf{E}(c_2 | c_2 \leq \overline{c}_2)$$

for two distinct values of c_1 since the right-hand side is strictly increasing in c_1. Thus, $\overline{c}_2$ must increase strictly in response to an increase in c_1. This demonstrates the Concorde effect because for any fixed X, the probability that the project will be completed (conditional on having been initiated) is $\Pr\left(c_2 \leq \overline{c}_2(c_1)\right)$, which we have shown is strictly increasing in c_1.

C. *Other Models of Decision Making*

The optimal initiation strategy is sophisticated and takes the completion strategy into account. But an investor who suffers from limited memory may not be forward-looking. Naïvete comes in many forms but in one version, the investor believes he will complete all initiated projects. A naïve investor maximizes:

$$\int_0^\infty (X - c_2) f(c_2) dc_2 - c_1.$$

When the cost of initiation is c_1, the naïve investor will initiate any project with a reward X that is greater that a threshold

$$\overline{X}(c_1) \equiv c_1 + \mathbf{E}(c_2).$$

In Figure 1, the naïve initiation strategy is simply a horizontal line whose position depends on the realized initiation cost c_1.

At the second stage, the investor realizes he has limited memory and also comes to terms with his naïvete. The completion strategy is backward-looking: as the naïve initiation strategy is independent of the completion strategy, the investor can deduce the threshold $\overline{X}(c_1)$ employed at the first stage for the realized cost of initiation c_1. As before, he completes the project if and only if

$$c_2 \leq \mathbf{E}(X | X \geq \overline{X}(c_1)).$$

The equilibrium is given by the unique intersection of the completion strategy and the naïve initiation strategy. As the naïve initiation strategy increases with the initiation cost, so does the equilibrium. The Concorde effect appears in this model of naïve decision-making. In fact, the Concorde effect is present in any model with the following two properties. First, the optimal initiation strategy is a threshold policy which is independent of the completion strategy and the threshold is increasing in c_1. Second, the completion strategy is a threshold policy that is increasing in $\overline{X}$. For example, the first property holds if the naïve investor believes he has full memory, so the probability of completion is lower the higher is the completion cost c_2. The second property holds if the completion strategy remains as above. Hence, the Concorde effect is also present in this alternative model of naïvete.

D. *Imperfect Memory*

Our model assumes that profits are forgotten but that sunk costs are remembered. A more general model would allow either or both to be remembered with positive probability. The results are unchanged in such a model because sunk costs will convey information that is valuable in the second stage only in the event that profits are forgotten and sunk costs remembered, which is the case we have studied.

To demonstrate formally, let $\mathcal{M} = \{(c_1, X), (\emptyset, X), (c_1, \emptyset), (\emptyset\, \emptyset)\}$ denote the possible memories in the second stage about (c_1, X). Here $\emptyset$ indicates that the corresponding variable has been forgotten. Assume some probability distribution $q(m)$ giving the probability of memory $m \in \mathcal{M}$. The investor's strategy now consists of a threshold for X in the first stage, and four thresholds for c_2 in the second stage, $\{\overline{c}_2(m)\}$, one for each memory $m \in \mathcal{M}$.

The expected payoff conditional on realized c_1 is given by

$$\Pi(\overline{X}, \{\overline{c}_2(m)\} | c_1) = \int_{\overline{X}}^{\infty} \sum_{m \in \mathcal{M}} q(m) \int_0^{\overline{c}_2(m)} (X - c_2) f(c_2)\, dc_2 - c_1 g(X)\, dX$$

$$= \int_{\overline{X}}^{\infty} \sum_{m \in \mathcal{M}} q(m) \int_0^{\overline{c}_2(m)} (X - c_2) f(c_2) g(X)\, dc_2\, dX - (1 - G(\overline{X}))c_1.$$

For any c_1, c_1', and any collection of thresholds $(\overline{X}, \{\overline{c}_2(m)\}_{m \varepsilon \mathcal{M}})$, the following version of equation (7) continues to hold,

$$\Pi(\overline{X}, \{\overline{c}_2(m)\} \mid c_1') = \Pi(\overline{X}, \{\overline{c}_2(m)\} \mid c_1) - \big(1 - G(\overline{X})\big)(c_1' - c_1),$$

so that we can apply a version of the argument from Proposition 2 to show the Concorde effect.

We could also consider more general models of imperfect memory, say where memories of sunk costs and profits were noisy. Characterizing the optimal strategy in these models becomes difficult because they lose the separability across different values of c_1 that we have exploited in our arguments. Nevertheless, it is a general property of these models that even the noisiest memory of sunk costs will be useful information about profits provided profits are not remembered perfectly.[8]

II. The General Case and the Pro-Rata Effect

Next we take up the general case in which the realized initiation cost also conveys information about the long-run profits of the project. Formally, we assume affiliation between c_1 and $-X$. This does not change the analysis of the full-memory benchmark but it introduces a second effect in the limited memory model which we call the pro-rata effect. A project with a higher initiation cost will have lower long-run profits on average and, other things equal, this reduces the incentive to complete the project. Of course this ignores the selection effect due to the investor's initiation strategy and there are non-trivial interactions between the strategies in the two stages. We show how to decompose the total sunk-cost bias into the Concorde and pro-rata effects and demonstrate that either can outweigh the other. Our theory is therefore able to explain both the Concorde and pro-rata biases.

Recall that $g(\cdot \mid c_1)$ is the conditional density of X conditional on a realized value of c_1. To extend our analysis to the general case, we modify the definitions of the reaction functions so that they are indexed both by the initiation cost c_1 and the density g of X. For the moment we treat these inputs separately in order to study independently the direct effect of a change in the initiation cost from the indirect effect of the change in the distribution of profits. The reaction functions are as follows:

$$\tilde{X}(\overline{c}_2 \mid c_1) = \frac{c_1}{F(\overline{c}_2)} + \mathbf{E}(c_2 \mid c_2 \leq \overline{c}_2) \tag{8}$$

$$\tilde{c}_2(\overline{X} \mid g) = \mathbf{E}_g(X \mid X \geq \overline{X}). \tag{9}$$

Notice that the parameter c_1 influences only the first formula and the distribution g influences only the second. Thus, the direct effect of an increase in c_1 will be captured entirely by an upward shift in the $\tilde{X}$ reaction function, exactly as in the case of independence. Now consider a shift in the distribution of X from a density g to another density

[8] Decomposing the sign of the effect of these memories on completion decisions, as we have done here, may be less straightforward in a general model.

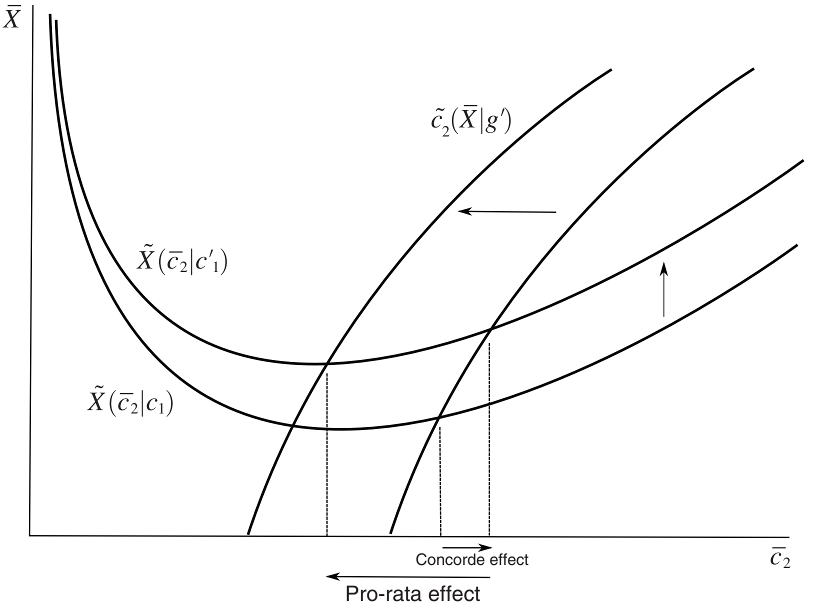


Figure 3. The Concorde and Pro-Rata Effects

g', which is smaller in the sense of MLRP. Recall that affiliation implies that an increase in c_1 has such an effect on the distribution of X. This reduces $\mathbf{E}_g(X|X \geq \overline{X})$ at every value of $\overline{X}$. Thus, the indirect effect of an increase in c_1 is entirely captured by a leftward shift of the $\tilde{c}_2$ reaction function. Figure 3 illustrates these effects in a simple setting in which the reaction curves intersect in only one point. We see that the direct effect produces a Concorde effect, and the indirect effect produces a pro-rata effect. The total effect is the sum of these and can be either a net Concorde bias or a net pro-rata bias.

As before, the general analysis is complicated by the multiplicity of intersection points. The formal proof demonstrates that these monotonicities are preserved even when a change in c_1 results in a shift from one equilibrium to another. [9] The results for the general model are described below.

PROPOSITION 3: *In the general model, the direct effect of a change in initiation costs is a Concorde effect. Under affiliation, the indirect effect through the distribution of profits is a pro-rata effect. The total effect can be either a Concorde bias or a pro-rata bias depending on parameters.*

PROOF:

The direct effect of an increase in the cost of initiation from c_1 to c_1' is found by holding the distribution $g = g(\cdot\,|\,c_1)$ constant and analyzing the effect of changing only c_1. In particular, this leaves the $\overline{c}_2$ reaction equation unchanged and shifts only the $\overline{X}$ reaction equation. This analysis is equivalent to the case in which X is

[9] The proof is also more complicated because the simple argument behind Proposition 2 used the fact that the distribution over X was constant as c_1 changed, allowing us to derive equation (7).

independent of c_1, so we can apply our previous result to establish that the direct effect is a Concorde effect. Next, to analyze the indirect effect, we hold c_1 constant and consider the effect of a change in the distribution of X from $g(\cdot \mid c_1)$ to $g(\cdot \mid c_1')$. This defines the reaction equation for $\overline{X}$:

$$\int_0^{\overline{c}_2} (\tilde{X}(\overline{c}_2 \mid c_1) - c_2) f(c_2) dc_2 - c_1 = 0.$$

We can then characterize an optimal second-stage threshold $\overline{c}_2$ as the solution to the following profit maximization:

$$\max_{\overline{c}_2} V(\overline{c}_2, g) := \int_0^{\infty} W(X, \overline{c}_2) g(X \mid c_1) dX$$

$$\text{s.t.} \quad W(X, \overline{c}_2) = 1_{X \geq \tilde{X}(\overline{c}_2 \mid c_1)} \left[\int_0^{\overline{c}_2} (X - c_2) f(c_2) dc_2 - c_1 \right],$$

where $1_{X \geq \tilde{X}(\overline{c}_2 \mid c_1)}$ is the indicator function for the event $X \geq \tilde{X}(\overline{c}_2 \mid c_1)$, i.e. the event that X is large enough for the project to be initiated.[10] The schedule $W(X, \overline{c}_2)$ gives the expected profit as a function of X. The threshold $\overline{c}_2$ affects the schedule in two ways. First, it determines the costs incurred in the second stage. Second, it affects the $\overline{X}$ threshold via the reaction function $\tilde{X}(\overline{c}_2 \mid c_1)$. This formulation therefore implicitly adjusts $\overline{X}$ to its optimal value given $\overline{c}_2$, and thus reduces the profit-maximization problem to a single choice variable, $\overline{c}_2$. From the definition of $\tilde{X}(\overline{c}_2 \mid c_1)$, we can rewrite $W(X, \overline{c}_2)$ as follows:

$$W(X, \overline{c}_2) = \max \left\{ 0, \int_0^{\overline{c}_2} (X - c_2) f(c_2) dc_2 - c_1 \right\}.$$

Notice that for any $\overline{c}_2$, the schedule $W(X, \overline{c}_2)$ as a function of X, has two linear segments. It is flat at zero for all $X \leq \overline{X}(\overline{c}_2)$, and then increasing with a slope of $F(\overline{c}_2)$ for $X > \overline{X}$. See Figure 4(a). This allows us to rule out as potential optima those values of $\overline{c}_2$ that are on a decreasing section of the $\overline{X}$ reaction curve. Recall we fix c_1 and consider two thresholds $\overline{c}_2' > \overline{c}_2$ such that $\overline{X}(\overline{c}_2') < \overline{X}(\overline{c}_2)$. Then the observation in the previous paragraph shows that $\overline{c}_2'$ *dominates* c_2 in the following sense: the schedule $W(X, \overline{c}_2')$ lies everywhere (weakly) above $W(X, \overline{c}_2)$ (and strictly above throughout the increasing region of $W(X, \overline{c}_2')$ as $F(\overline{c}_2') > F(\overline{c}_2)$). Whatever the realization of X, the thresholds $\overline{c}_2'$ and $\overline{X}(\overline{c}_2')$ give higher expected profits ex ante than the thresholds $\overline{c}_2$ and $\overline{X}(\overline{c}_2)$. The thresholds $\overline{c}_2$ and $\overline{X}(\overline{c}_2)$

[10] This is expressed as an ex ante optimization, i.e., calculating the expected payoff form employing a completion threshold $\overline{c}_2$ prior to the realization of X and c_2. Any ex ante optimal strategy must induce an interim optimal strategy, i.e., optimal after the realization of X and c_2. In view of Proposition 1 it is valid to analyze optimal strategies in this problem of imperfect recall.

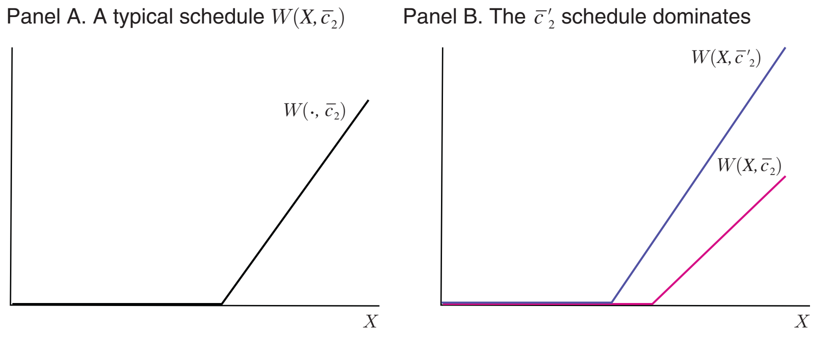


Figure 4. The Profit Schedule

cannot be optimal. See Figure 4, panel B. We can thus restrict attention to the following set of $\overline{c}_2$ values

$$\mathcal{K} = \{\overline{c}_2 : \overline{c}'_2 > \overline{c}_2 \text{ implies } \overline{X}(\overline{c}'_2) > \overline{X}(\overline{c}_2)\},$$

and analyze the following optimization problem

$$\max_{\overline{c}_2 \in \mathcal{K}} V(\overline{c}_2, g) := \int_0^{\infty} W(X, \overline{c}_2) g(X \mid c_1) dX.$$

We are going to demonstrate the pro-rata effect by applying a monotone comparative statics result due to Susan Athey (1998) to show that smaller values of g correspond to smaller optimal choices of $\overline{c}_2$. The relevant result is reproduced below. Let X be a totally ordered set. A real-valued function $h : X \to \mathbf{R}$ satisfies *weak single-crossing in one variable* if there exists $x' \in X$ such that $h(x) \leq 0$ for all $x < x'$ and $h(x) \geq 0$ for all $x > x'$. The function satisfies *single-crossing in one variable* if there exist $x' < x''$ such that $h(x) < 0$ for all $x < x'$, $h(x) = 0$ for all $x' < x < x''$, and $h(x) > 0$ for all $x > x''$. A real-valued function $h : X \times C \to \mathbf{R}$ satisfies *single-crossing in two variables* if, for all $c' > c$, the function $h(\cdot, c') - h(\cdot, c)$ satisfies single-crossing in one variable. A family $\{g(\cdot \mid c)\}_{c \in \mathcal{I}}$ of probability density functions over X is totally ordered by the monotone likelihood ratio property (MLRP) if the ratio

$$\left(\frac{g(x' \mid c')}{g(x' \mid c)} \right)$$

is non-decreasing in x' whenever $c' > c$. It is well known that if two random variables x' and c, jointly distributed according to F are affiliated, then the family of conditional distributions $F(x' \mid c)$ is totally ordered by MLRP.

PROPOSITION 4: *Athey* (1998, *Extension* (*iii*) *of Theorem* 3) *Let* $\delta(X)$ *be a real-valued function satisfying weak single-crossing in one variable and let* $\{g(X)\}$ *be a*

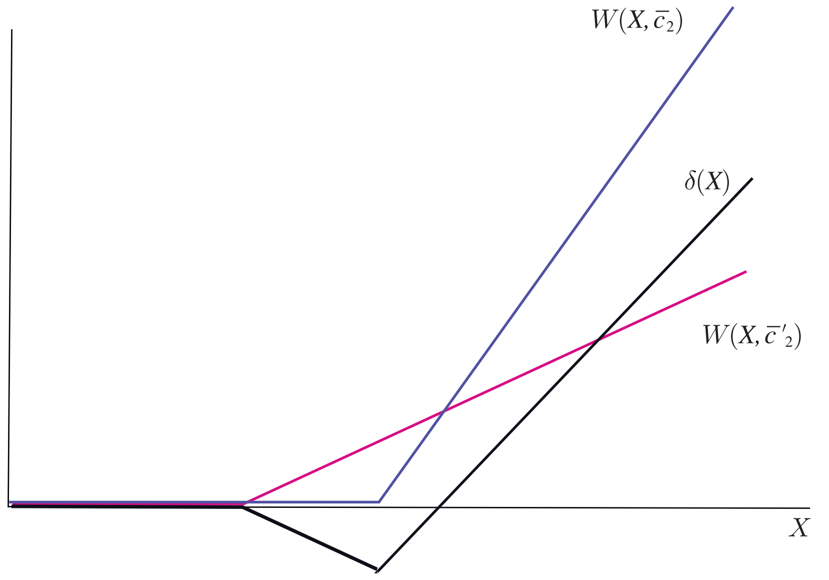


Figure 5. The Difference $\delta(X) = W(X, \bar{c}_2) - W(X, \bar{c}'_2)$ Satisfies Weak Single-Crossing in One Variable

family of probability density functions over X, having the same support and ordered by MLRP. Then the function

$$\Delta(g) := \int_0^{\infty} \delta(X) g(X) dX$$

satisfies single-crossing in the variable g.

Consider a pair of values $\bar{c}_2$, $\bar{c}'_2$ in $\mathcal{K}$, and suppose $\bar{c}_2 > \bar{c}'_2$.[11] Consider the point-wise difference

$$\delta(X) = W(X, \bar{c}_2) - W(X, \bar{c}'_2).$$

By the properties of the profit schedules discussed above, $\delta(X)$ satisfies weak single-crossing in one variable, i.e., there exists a X_0 such that $\delta(X) \geq 0$ for all $X \geq X_0$ and $\delta(X) \leq 0$ for all $X \leq X_0$. Figure 5 illustrates.

Thus by Proposition 4, the difference in expected profits, viewed as a function of the distribution g

$$\Delta(g) = V(\bar{c}_2, g) - V(\bar{c}'_2, g)$$

[11] If $\mathcal{K}$ is a singleton, then its single element is the only candidate for an optimum and monotonicity of the optimum in c_1 is trivially guaranteed.

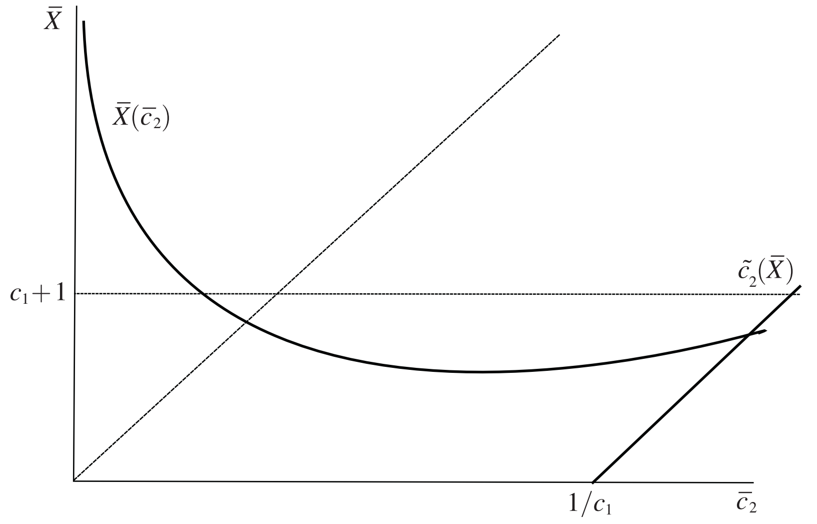


Figure 6. Reaction Curves for the Exponential Distribution

satisfies single-crossing in the variable g, ordered by MLRP. This, in turn, establishes that the family of profit functions

$$\{V(\overline{c}_2, g) \mid \overline{c}_2 \in \mathcal{K}\}$$

satisfies single-crossing in two variables and by the monotone comparative-statics result of Paul Milgrom and Chris Shannon (1994), the set of maximizers

$$\arg\max_{\overline{c}_2 \in \mathcal{K}} \; V(\overline{c}_2, g)$$

is non-decreasing (in g ordered by MLRP) in the strong set-order. By the affiliation of c_1 and $-X$, the distribution $g(\cdot \mid c_1')$ is smaller than $g(\cdot \mid c_1)$ in the MLRP sense when $c_1' > c_1$. This establishes the pro-rata effect.

A. *Example*

Here is an example which shows that the net effect can be a Concorde or pro-rata bias. Let X be distributed according to the exponential distribution with parameter c_1. Let c_2 be distributed according to the exponential distribution with parameter 1. The distribution of c_1 is irrelevant. The reaction equations (see equation (8) and equation (9)) are

$$\tilde{X}(\overline{c}_2 \mid c_1) \;=\; \frac{c_1 \;-\; e^{-\overline{c}_2}(\overline{c}_2 \;+\; 1) \;+\; 1}{1 \;-\; e^{-\overline{c}_2}}$$

$$\tilde{c}_2(\overline{X} \mid c_1) \;=\; \overline{X} \;+\; \frac{1}{c_1}.$$

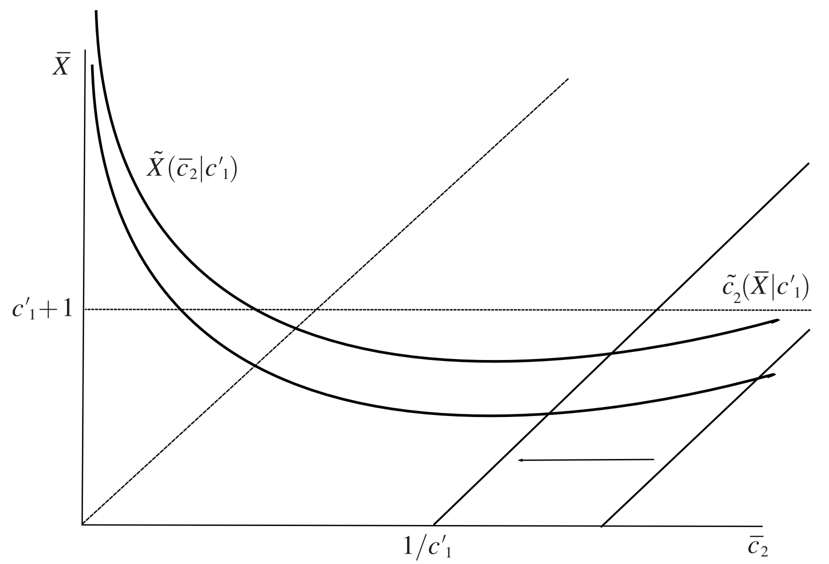


Figure 7. Pro-Rata Effect Dominates for Small c_1

For any value of c_1, the $\tilde{X}(\overline{c}_2)$ reaction function first declines with $\overline{c}_2$ and then increases. As $\overline{c}_2$ increases, there is a horizontal asymptote at $c_1 + 1$. The $\tilde{c}_2(\overline{X})$ reaction function has a linear graph with unit slope and intercept equal to $1/c_1$. These are illustrated in Figure 6.

We can see that for small values of c_1, the unique equilibrium (and therefore the optimum) value of $\overline{c}_2$ is also large. Projects with low initiation costs will be completed with high probability. Now consider the effect of a small increase in the initiation cost. Because c_1 was low, the intercept $1/c_1$ of the $\tilde{c}_2(\overline{X})$ reaction curve will fall rapidly in response to a small increase in c_1. See Figure 7. On the other hand, in the neighborhood of the original equilibrium, the $\tilde{X}(\overline{c}_2 | c_1)$ reaction function is approximately horizontal at $c_1 + 1$ and therefore a small increase in c_1 results in only a small upward shift in the neighborhood of the equilibrium.

It follows that, starting from low initiation costs, the effect of an increase in the initiation cost is a shift leftward of the intersection point and hence a reduction in $\overline{c}_2$. The pro-rata effect dominates at small values of c_1.

Now, when c_1 is large, the $\tilde{c}_2(\overline{X} | c_1)$ reaction function is close to its limit, the 45° line, so further increases in c_1 keeps this curve roughly constant. Thus, the pro-rata effect shuts down for large values of c_1, whereas the $\tilde{X}(\overline{c}_2 | c_1)$ reaction curve continues to shift upward. Thus, for projects with large initiation costs (for example transatlantic super-sonic jets), the Concorde effect dominates, as illustrated in Figure 8.

These intuitions are confirmed in Figure 9. The figure plots a numerical solution to the reaction equations, giving the $\overline{c}_2$ threshold as a function of c_1. The U-shape demonstrates that the pro-rata effect dominates for small c_1 but is eventually outweighed by the Concorde effect as c_1 increases.

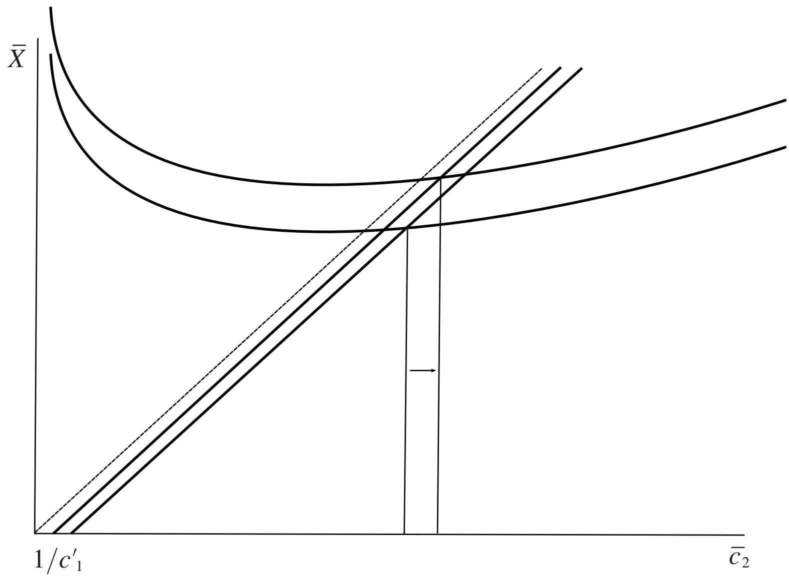


FIGURE 8. CONCORDE EFFECT DOMINATES FOR LARGE c_1

III. Experimental Results

We tested a simplified version of our model experimentally in order to verify the relationship between limited memory and sunk-cost bias. Ours is evidently the first laboratory experiment of a sequential investment problem examining sunk-cost effects. Our experiment consists of a baseline treatment in which memory is unconstrained and the treatment of interest in which we induced a memory constraint. We measure and sign the baseline bias in order to compare with the magnitude and direction of the bias induced by our limited memory treatment. In addition, the baseline treatment is of independent interest in itself in light of the experimental literature on sunk-cost bias. The results lend partial support to the theory but they also raise some questions.

In the baseline treatment our subjects exhibit the pro-rata bias. This result is of independent interest because most experimental studies of sunk-cost fallacies focus on the Concorde bias. For example, the field experiment of Arkes and Blumer (1985) reveals a Concorde bias. When payoffs are controlled to the extent possible in our laboratory setting, and when the size of monetary sunk and incremental costs are directly observed, we find instead a significant and large pro-rata bias.

The pro-rata bias we observe in the experiment is inconsistent with a simple reading of our theory. Our theory predicts no sunk cost bias, either the Concorde effect or the pro-rata bias, should be observed in the full memory treatment. As discussed in the introduction we find it plausible to suppose that sunk-cost bias evolved as a heuristic which is well adapted to the typical decision problems encountered in the environment, including memory constraints. Under that interpretation, our baseline treatment is measuring the direction and magnitude of the background heuristic.

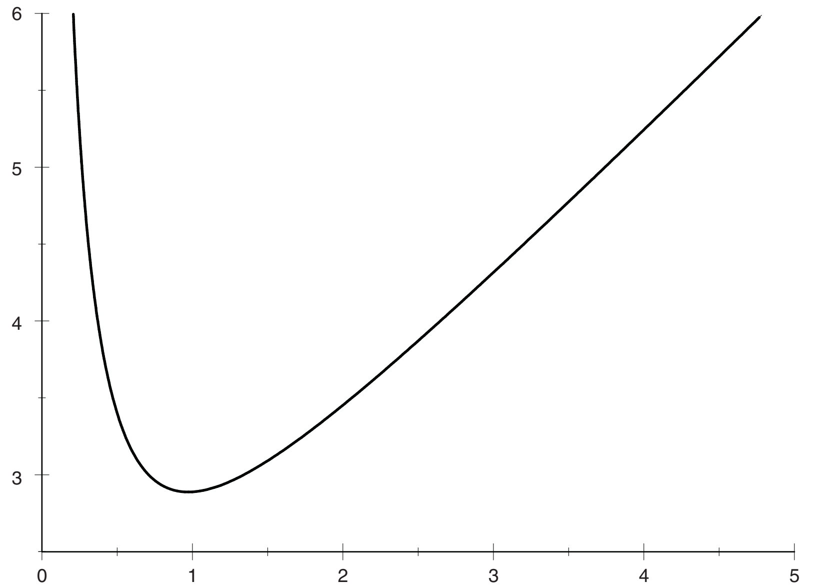


FIGURE 9. $\overline{c}_2(c_1)$ FROM THE EXAMPLE

In our limited memory treatment, the subjects exhibit the Concorde bias as predicted by the theory. One possible explanation for the reversal of the sunk cost heuristic is based on the idea of *fast and frugal heuristics* described by Gigerenzer and Goldstein (1996). They describe a decision-making procedure based on a hierarchy of heuristics. A default heuristic, here the pro-rata bias, is one that is best adapted to the typical environment. When confronted with a novel cue, here the artificial memory constraint, the decision maker searches for the heuristic that is most applicable to the problem at hand, in this case the Concorde bias.

This interpretation goes well beyond the formal details of our model. It also suggests that further experiments are needed to elicit which heuristics are common and how a decision maker switches among them as he learns about the underlying environment.

A. *Experimental Model*

In our simplified model, all distributions have two-point support with equal probability. The value of the project X is either 7 or 12, the initiation cost c_1 is either 1 or 6 and the completion cost c_2 is either 1 or 10. All distributions are independent, implying by our theoretical results that limited memory should produce a Concorde effect.

To induce limited memory we employed the following design. At the initiation stage, two independent random draws from $\{7, 12\}$ were conducted and the subject was informed of the two realizations. Denote by $\sigma = (\sigma_1, \sigma_2)$ the realized values. Next, one of these signals, say σ_1 was selected at random and the subject was informed that the value of the project was equal to this selected value $X = \sigma_1$. In addition c_1 was randomly drawn from $\{1, 6\}$ and the subject was informed of its

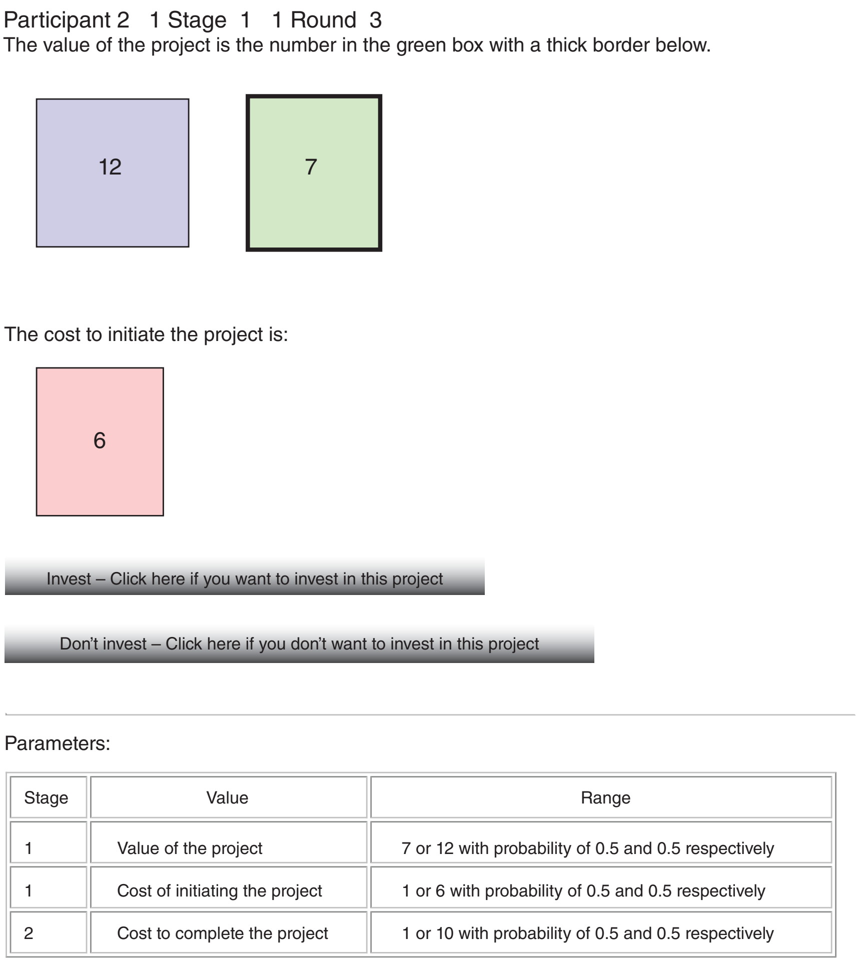
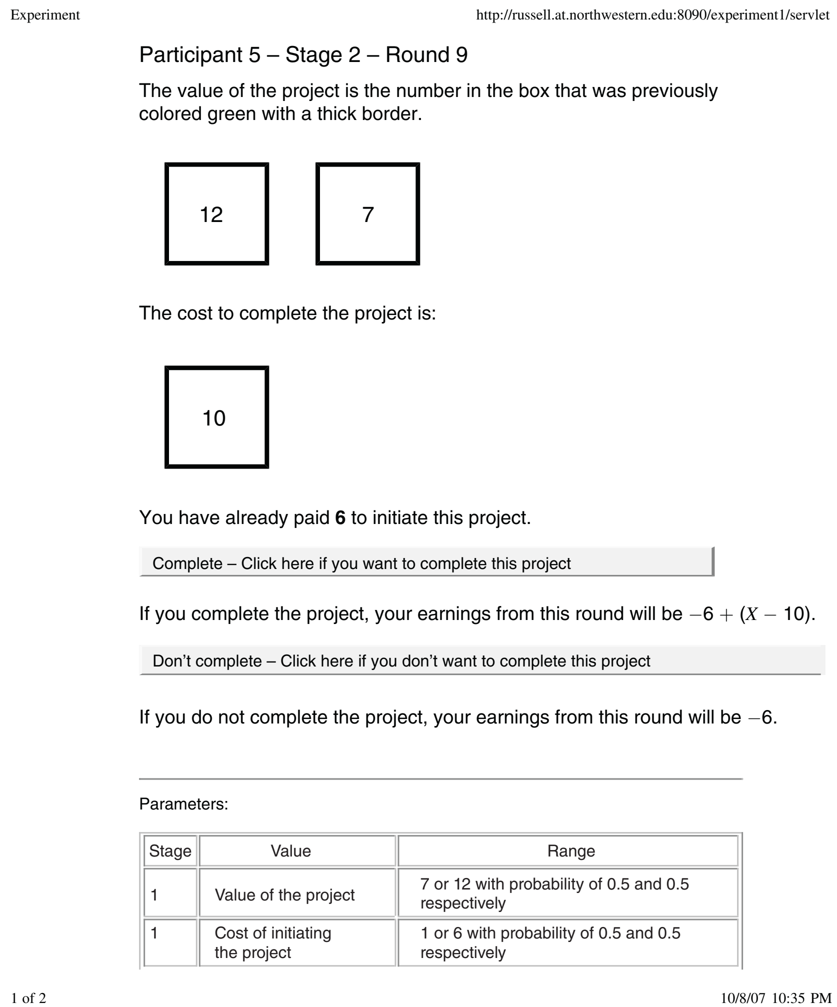


Figure 10A. Experiment: Initiation Stage

value. Finally, the subject was informed that the completion cost c_2 would be drawn randomly from $\{1, 10\}$ in the second stage if the subject chose to initiate the project. The subjects were given detailed instructions outlining the timing of the game and the payoffs and they were informed of all the distributions. Figure 10A displays the decision screen presented to the subjects in the initiation stage.

Each subject played 20 distinct trials. To induce limited memory we first had the subjects play through the initiation stage of each of the 20 trials and then after all of the initiation decisions were made, the subjects returned to the completion stage of all those projects which had been initiated in the first stage. This structure makes it very difficult to remember the actual value of X for each project. At the completion stage, the subjects were reminded only the *pair* of signals (σ_1, σ_2) and the initiation cost c_1. They were not reminded which of the two signals contained the actual project value X. Next the subjects were informed of the realized completion cost and were given the decision of whether to complete the project. Figure 10B displays the screen presented to the subjects at the completion stage.


Experiment http://russell.at.northwestern.edu:8090/experiment1/servlet

Participant 5 – Stage 2 – Round 9

The value of the project is the number in the box that was previously colored green with a thick border.

12 7

The cost to complete the project is:

10

You have already paid **6** to initiate this project.

Complete – Click here if you want to complete this project

If you complete the project, your earnings from this round will be $-6 + (X - 10)$.

Don't complete – Click here if you don't want to complete this project

If you do not complete the project, your earnings from this round will be -6.

Parameters:

Stage	Value	Range
1	Value of the project	7 or 12 with probability of 0.5 and 0.5 respectively
1	Cost of initiating the project	1 or 6 with probability of 0.5 and 0.5 respectively

1 of 2 10/8/07 10:35 PM

Figure 10B. Experiment: Completion Stage

With this design, the baseline treatment consists of those rounds in which $\sigma_1 = \sigma_2$ so that the subject is perfectly informed of the project's value at the completion stage. An example is illustrated in Figure 10C. In the baseline treatments, optimal behavior would ignore sunk costs and complete the project if and only if $X > c_2$.

When $\sigma_1 \neq \sigma_2$ the subject has limited memory of X: he knows only that it is either σ_1 or σ_2. Here is an analysis of optimal behavior in these treatments. First, all projects with $c_2 = 1$ should be completed because X always exceeds 1. Note that this completion decision is optimal no matter what the subject remembers about X. Next, all projects should be initiated except those for which $X = 7$ and $c_1 = 6$. To see this, note that when $X = 7$ and $c_1 = 6$, regardless of the completion decision, the project will produce a negative payoff. In the best case, $c_2 = 1$ and the net value is $X - c_1 - c_2 = 7 - 6 - 1 = 0$, and when $c_2 = 10$ the project would have a negative value if completed.

Experiment http://russell.at.northwestern.edu:8090/experiment1/servlet

Participant 5 – Stage 2 – Round 16

The value of the project is the number in the box that was previously colored green with a thick border.

12 12

The cost to complete the project is:

10

You have already paid **6** to initiate this project.

Complete – Click here if you want to complete this project

If you complete the project, your earnings from this round will be $-6 + (X - 10)$.

Don't complete – Click here if you don't want to complete this project

If you do not complete the project, your earnings from this round will be -6.

Parameters:

Stage	Value	Range
1	Value of the project	7 or 12 with probability of 0.5 and 0.5 respectively
1	Cost of initiating the project	1 or 6 with probability of 0.5 and 0.5 respectively

1 of 2 10/8/07 10:42 PM

FIGURE 10C. EXPERIMENT: BASELINE TREATMENT

Consider the case of $X = 12$ and $c_1 = 6$. By the previous argument, we know that this project would be completed regardless of c_2. This is because the subject will remember $c_1 = 6$ and infer that $X = 12$. Thus, the expected second stage cost is $\mathbf{E}c_2 = (1 + 10)/2 = 5.5$ and the expected profit of this project is $X - c_1 - \mathbf{E}c_2 = 12 - 6 - 5.5 > 0$ and this project should be initiated.

Finally, consider the case of $c_1 = 1$. These projects should be initiated because they will be completed whenever $c_2 = 1$. In particular, if $X = 7$, the worst-case profit would be if the project were completed at $c_2 = 10$ but even in this case, the expected profit is $7 - 1 - 5.5 > 0$. And if $X = 12$ the worst-case is that the project is not completed when $c_2 = 10$. That gives an expected profit of $½(12 - 1) - 1 > 0$.

Notice that this initiation strategy is optimal regardless of what the investor expects to remember about X in the second stage, and therefore regardless of what we assume the investor expects to remember.[12] This is important experimentally because, although we gave complete instructions about the information structure of the game, the subjects may differ in their memory capacity and their beliefs about their memory capacity. Regardless of this heterogeneity, the initiation strategy we have outlined is optimal.

We turn now to the second stage. Because of this uniquely optimal first-stage behavior, optimal behavior in the second stage is trivial in all but one case. We have already shown that all projects with $c_2 = 1$ should be completed. When $c_2 = 10$ and the investor remembers that $c_1 = 6$, he can infer from the optimal first-stage behavior that $X = 12$ and it is optimal to complete the project.

The interesting case is $c_2 = 10$ and $c_1 = 1$. In this case, the first-stage behavior yields no conclusive inference about X. If the subject has no memory of X (as we expect from our design) then the value of the project is $(7 + 12)/2 = 9.5$ in expectation and it is not optimal to incur a completion cost of $c_2 = 10$. On the other hand, if the subject does remember that $X = 12$ (an unlikely possibility but one we cannot rule out) then he should complete the project.

With this analysis in hand we can state our main experimental hypotheses. They concern the situation in which the project has been initiated and $c_2 = 10$. In the limited memory treatment $\sigma_1 \neq \sigma_2$, subjects who do not recall X will complete the project when $c_1 = 6$ but not when $c_1 = 1$. They exhibit the Concorde effect. Thus, under the assumption that our design indeed imposed a memory constraint on *some* of our subjects (but without making any assumption about their fraction in the subject pool), our hypothesis is that when $c_2 = 10$ and $\sigma_1 \neq \sigma_2$ the completion probability when $c_1 = 6$ is higher than when $c_1 = 1$.

B. *Empirical Results*

We recruited 100 subjects to take part in the experiment. The subjects were MBA students at Kellogg Graduate School of Management. Most students were in the second quarter of their first year. The students were early in the program and hence unlikely to have encountered the idea that costs once sunk should be ignored in making subsequent decisions. None knew our theory of the sunk cost fallacy. The subjects were given detailed instructions about the timing of decisions, the distributions of parameters, the information structure, and payoffs. These instructions were read aloud and were displayed to the subject on screen during the experiment. The instruction sheet is reproduced in Figures 10D and 10E. The subjects first played 10 trial rounds with full memory prior to the 20 rounds of interest. We use only the data from these latter 20 rounds.

Each subject was given an initial endowment of 140 points to which further points were added or subtracted by their realized play in the experiment. Points were converted to dollars at an exchange rate of 2 points = \$1. The subjects were told these details and also told that they would have an approximately 20 percent chance of

[12] The conclusion that all $c_2 = 1$ projects will be completed requires no assumption about memory, and this conclusion plus its implications are the only properties of second-stage behavior that were used in the preceding calculations.

You will participate in an experiment that will unfold in several stages.

Stage 1

First, you will see 2 numbers in blue boxes which are equally likely possible "values of the project."

The values can be 7 or 12 with probability 0.5 and 0.5 respectively.

Next, one of these boxes will be highlighted in green with a thick border to show the realized value of the project.

Finally, you will see a number in a pink box which is the "cost of initiating the project."
The cost can be 1 or 6 with probability 0.5 and 0.5 respectively.
Let's denote the realized cost of initiation by c_1.

There are two buttons marked "Invest" and "Don't Invest"

If you click "Don't Invest", this round of the experiment is over and your payoff is zero.
If you click "Invest", your payoff will be determined by a decision you make in stage 2.

Example. Assume the cost of initiation is 6. If you "Don't Invest," your payoff is zero. If you "Invest," your payoff is determined in stage 2.

The entire experiment will involve 30 projects. You will first complete stage 1 for each of the 30 projects before moving on to stage 2.

Stage 2

In stage 2, you will decide whether to complete the projects you chose to initiate in stage 1.

For each of these projects you will be reminded of the cost you paid in stage 1. In the first 10 rounds you will also be reminded of the value of the project.

Then you will see a number in a pink box which is the "cost to complete the project."
The cost can be 1 or 10 with probability 0.5 and 0.5 respectively.

Figure 10D. Instructions Page 1

getting paid according to their performance. Twenty subjects were randomly chosen and paid. No subject went bankrupt during the experiment. The highest payment was $119 and the lowest was $78.

Table 1 describes the completion rates conditional on $c_2 = 10$ which is the case of interest.[13]

[13] When $c_2 = 1$ the project should always be completed and the subjects completed these projects 950 times out of 960 occurrences.

There are two buttons marked "Complete" and "Don't Complete."

Regardless of which option you select, you will lose the cost c_1 which you already chose to pay in stage 1.

If you click "Don't Complete," there are no additional costs or earnings and so your total payoff will be $-c_1$.

If you click "Complete," then you will earn an amount equal to the value of the project AND in addition to the cost c_1 already incurred, you will also incur the cost of completion. Your total payoff will therefore be the value minus both c_1 and the cost of completion.

This completes this round of the experiment (unless it was already ended by a "Don't Invest" decision in stage 1).

Example. Assume the value is 7 and the cost of initiation is 6 and that you invested in stage 1. Your cost of completion is 10. If you "Don't Complete," your payoff is -6. If you "Complete," your payoff is $7 - 6 - 10 = -9$.

Start the first round

Figure 10E. Instructions Page 2

A comparison of the first two columns reveals the baseline pro-rata bias. Conditional on reaching the second stage, subjects were more likely to complete the project when the sunk cost was low. In the last two columns we see the opposite effect for the limited memory treatments. Here subjects exhibit the Concorde bias as they are more likely to complete projects when the sunk cost was high.[14]

The Concorde effect must be large enough to overwhelm the background pro-rata bias. To uncover the size of the Concorde effect, we control for the pro-rata bias in two ways.

In our first approach, we use the scenario where $c_2 = 10$ and $\sigma_1 = \sigma_2 = 12$ to estimate the pro-rata fallacy. A subject facing this problem has *de facto* full memory: he knows the project is worth 12. If he does not exhibit the pro-rata fallacy, only the cost $c_2 = 10$ will affect his completion decision and he will complete the project regardless of the cost of initiation. If the subject does exhibit the pro-rata bias, he will add the cost of initiation to the cost of completion. He will complete the project if $c_1 = 1$ but not when $c_1 = 6$. Thus, we take the difference in the completion rates when $c_2 = 6$ and $c_2 = 1$ as a measure of the pro-rata bias. It is negative when subjects display the pro-rata bias. This difference in completion rates is higher and in fact positive in the limited memory treatment where σ_1

[14] The second stage decision in the limited memory cases is statistically uncorrelated with other stage 1 information that is unavailable to the subject in stage 2. This is to be expected from our design and confirms that limited memory was successfully induced.

Table 1—Summary Statistics of Experimental Results

	Benchmark $\sigma_1 = \sigma_2 = 12$		Limited memory $\sigma_1 \neq \sigma_2$	
	$c_1 = 1$	$c_1 = 6$	$c_1 = 1$	$c_1 = 6$
Observations	131	80	210	94
Number completed	118	46	71	40
Completion rate	90 %	58 %	34 %	43 %

Note: These are completion decisions conditional on a project having been initiated and for completion cost $c_2 = 10$.

Table 2—Estimating the Concorde Effect $\mathcal{C}$

	Estimate	Bootstrap SE	Significance $P > z$
$\Delta\Pr(\text{complete}\vert\sigma_1 = \sigma_2 = 12)$	−0.33	0.07	0.000
$\Delta\Pr(\text{complete}\vert\sigma_1 \neq \sigma_2,$	0.09	0.07	0.183
$\mathcal{C}$	0.41	0.09	0.000

Note: Bootstrap standard errors with 1,000 replications.

Table 3

	Limited memory $c_1 = 1$	$\sigma_1 \neq \sigma_2$ $c_1 = 6$
Observations	78	44
Number completed	25	21
Completion rate	32%	50%

$\neq \sigma_2$. The difference in differences is our measure of the Concorde effect induced by limited memory:

$$\mathcal{C} = \Delta\Pr(\text{complete}\,|\,\sigma_1 \neq \sigma_2) - \Delta\Pr(\text{complete}\,|\,\sigma_1 = \sigma_2 = 12)$$

(where $\Delta\Pr(\text{complete}\,|\,\cdot)$ represents the completion rate when $c_1 = 6$ minus the corresponding completion rate when $c_1 = 1$).

In Table 2 we report estimates of both $\Delta\Pr(\text{complete}\,|\,\sigma_1 \neq \sigma_2)$ and $\Delta\Pr(\text{complete}\,|\,\sigma_1 = \sigma_2 = 12)$ as well as $\mathcal{C}$. The baseline pro-rata bias and the limited-memory induced Concorde effect $\mathcal{C}$ are large and highly significant.

In our second approach, we focus on subjects who never display the pro-rata effect in the full memory treatment. We study subjects who always complete the project when $c_2 = 10$ and $\sigma_1 = \sigma_2 = 12$. We exclude subjects who never encounter this configuration of parameters or sometimes cancel the project when they do. According to the theory, those subjects who have revealed no sunk cost bias in the full-memory benchmark should display a Concorde bias in the limited memory treatment. Table 3 summarizes the completion rates for these subjects in the limited memory treatment when the $c_2 = 10$. The completion rate is 18 percent higher when $c_1 = 6$ than when $c_1 = 1$ and the difference is statistically significant (Bootstrap Std. Error 0.09, Significance 0.059).

Table 4

Subject	Completion rate (%) $c_1 = 1$	Completion rate (%) $c_1 = 6$	Difference in completion rates (%)
1	0	100	100
2	33:3	100	66:7
3	100	100	0
4	0	100	100
5	33:3	100	66:7
6	100	100	0
7	50	100	50
8	33:3	0	−33:3
9	0	100	100
10	0	50	50
11	33:3	100	66:7
12	0	0	0
13	25	100	75
14	100	100	0
15	100	100	0
16	0	0	0
17	0	0	0
18	0	0	0
19	0	0	0
20	33:3	0	−33:3
21	0	0	0
		Average	29:0%

We also study this subset of the data by subject. We include subjects who encounter variation in the cost of initiation in the limited memory treatment. We exclude subjects who never observe any variation. Table 4 reports completion rates and the difference in completion rates by subject.

The average of the completion rate when $c_1 = 6$ minus the completion rate when $c_1 = 1$ is 29 percent for this subgroup. Under the Mann-Whitney test, this difference is significant at the 5.4 percent level. Notice that the difference in completion rates is positive for nine subjects and negative for two. Under a binomial test, this difference is significant at the 3.3 percent level.

Once we study subjects who never display the pro-rata fallacy, there is a large Concorde effect whether we study the data at the aggregate or the subject level.

In summary, all the approaches we take to control for the pro-rata fallacy point to a Concorde effect that is large and significant.

IV. Conclusion

Memory constraints are a potentially important source of a variety of behavioral regularities. In addition to those modeled in Wilson (2003), Benabou and Tirole (2004, 2006) and others, we have shown how sunk cost bias arises naturally as a strategy for coping with limited memory.

Our experimental design allows us to simulate memory constraints and investigate their impact on real decision-making. An interesting direction for future research is to adapt this experimental method to investigate self-control, overconfidence and self-signaling.

Appendix

Proof of Proposition 1

PROPOSITION 1: *An optimal strategy is a sequential equilibrium outcome of the game played between the first-stage and second-stage investor.*

PROOF:

Let s_1 denote an initiation strategy and s_2 a completion strategy. An overall strategy is denoted $s = (s_1, s_2)$. Consider an overall-optimal strategy s. Let $\mathcal{H}$ denote the collection of information sets in the second stage (including, for expositional convenience, the information set in which the project was not initiated). First, if there are any information sets that are not on the path of play under s, specify beliefs arbitrarily at those information sets, and modify s_2 to play a best response to those beliefs. This does not change the outcome induced by s since these histories arise with probability zero. For any second-stage information set h, write

$$\mathbf{E}\,\Pi(s_2\,|\,h)$$

for the conditional expected continuation payoff from following s_2 at information set h. By the law of total probability, we can express the overall payoff to s as follows,

$$\Pi(s) \;=\; \mathbf{E}_h\Big[\mathbf{E}\,\Pi(s_2\,|\,h)\Big], \tag{A1}$$

where the outside expectation is taken with respect to the distribution over second-stage information sets $\mathcal{H}$ induced by the first-stage strategy s_1. Now suppose that there was a second-stage strategy s_2' such that for a positive-probability collection of information sets H,

$$\mathbf{E}\,\Pi(\Pi(s_2'\,|\,h) \;>\; \mathbf{E}\,\Pi(s_2'\,|\,h)$$

for all $h \in \mathcal{H}$. Then it would follow immediately from equation A1 that $\Pi(s_1, s_2') > \Pi(s_1, s_2)$ which would contradict the overall optimality of s. Thus s is sequentially rational at second-stage information sets. Now, holding fixed s_2, the first-stage strategy s_1 affects only the distribution over second-stage information sets.[15] So, if there was a first-stage strategy s_1' which changed the distribution over $\mathcal{H}$ so as to increase the investor's payoff viewed from the first stage, i.e.,

$$\mathbf{E}_h[\mathbf{E}\,\Pi(s_2\,|\,h)],$$

then this would increase the overall payoff as well, again contradicting the overall-optimality of s. Thus, s is sequentially rational at all information sets.

[15] In an extensive-form game, payoffs are realized at terminal nodes. So while conceptually, the cost c_1 is incurred in the first stage, this is modeled by assuming that the initiation decision ensures that a terminal node will be reached which has a payoff reflecting the loss of c_1.

REFERENCES

Al-Najjar, Nabil, Sandeep Baliga, and David Besanko. 2008. "Market Forces Meet Behavioral Biases: Cost Misallocation and Irrational Pricing." *RAND Journal of Economics*, 39(1): 214–37.

Anand, Vikas, Charles C. Manz, and William H. Glick. 1998. "An Organizational Memory Approach to Information Management." *Academy of Management Review*, 23(4): 796–809.

Argote, Linda, Sara L. Beckman, and Dennis Epple. 1990. "The Persistence and Transfer of Learning in Industrial Settings." *Management Science*, 36(2): 140–54.

Arkes, Hal R., and Peter Ayton. 1999. "The Sunk Cost and Concorde Effects: Are Humans Less Rational Than Lower Animals?" *Psychological Bulletin*, 125(5): 591–600.

Arkes, Hal R., and Catherine Blumer. 1985. "The Psychology of Sunk Cost." *Organizational Behavior and Human Decision Processes*, 35(1): 124–40.

Athey, Susan. 1998. "Monotone Comparative Statics Under Uncertainty: Single-Crossing Properties and Log-supermodularity." Unpublished. http://kuznets.fas.harvard.edu/~athey/CSU0498.pdf.

Bailey, Charles D. 1989. "Forgetting and the Learning Curve: A Laboratory Study." *Management Science*, 35(3): 340–52.

Baliga, Sandeep, and Jeffrey C. Ely. 2011. "Mnemonomics: The Sunk Cost Fallacy as a Memory Kludge: Dataset." *American Economic Journal: Microeconomics*. http://www.aeaweb.org/articles.php?doi=10.1257/mic.3.4.35.

Benabou, Roland, and Jean Tirole. 2004. "Willpower and Personal Rules." *Journal of Political Economy*, 112(4): 848–86.

Benabou, Roland, and Jean Tirole. 2006. "Incentives and Prosocial Behavior." *American Economic Review*, 96(5): 1652–78.

Benkard, C. Lanier. 2000. "Learning and Forgetting: The Dynamics of Aircraft Production." *American Economic Review*, 90(4): 1034–54.

Darr, Eric D., Linda Argote, and Dennis Epple. 1995. "The Acquisition, Transfer and Depreciation of Knowledge in Service Organizations: Productivity in Franchises." *Management Science*, 41(11): 1750–62.

Dawkins, R., and T. R. Carlisle. 1976. "Parental Investment, Mate Desertion and a Fallacy." *Nature*, 262(5564): 131–33.

Ellison, Glenn, and Drew Fudenberg. 1993. "Rules of Thumb for Social Learning." *Journal of Political Economy*, 101(4): 612–43.

Eyster, Erik. 2002. "Rationalizing the Past: A Taste for Consistency." Unpublished.

Friedman, Daniel, Kai Pommerenke, Rajan Lukose, Garrett Milam, and Bernardo A. Huberman. 2007. "Searching for the Sunk Cost Fallacy." *Experimental Economics*, 10(1): 79–104.

Garland, Howard, Craig A. Sandefur, and Anne C. Rogers. 1990. "De-Escalation of Commitment in Oil Exploration: When Sunk Costs and Negative Feedback Coincide." *Journal Of Applied Psychology*, 75(6): 721–27.

Gigerenzer, Gerd, and Daniel G. Goldstein. 1996. "Reasoning the Fast and Frugal Way: Models of Bounded Rationality." *Psychological Review*, 103(4): 650–69.

Gould, S. J., and R. C. Lewontin. 1979. "The Spandrels of San Marco and the Panglossian Paradigm: A Critique of the Adaptationist Programme." *Proceedings of the Royal Society of London. Series B, Biological Sciences*, 205(1161): 581–98.

Govindarajan, Vijay, and Robert Anthony. 1983. "How To Use Cost Data in Pricing Decisions." *Management Accounting*, 65: 30–37.

Heath, Chip. 1995. "Escalation and De-escalation of Commitment in Response to Sunk Costs: The Role of Budgeting in Mental Accounting." *Organizational Behavior and Human Decision Processes*, 62(1): 38–54.

Hirshleifer, David, and Ivo Welch. 2002. "An Economic Approach to the Psychology of Change: Amnesia, Inertia, and Impulsiveness." *Journal of Economics and Management Strategy*, 11(3): 379–421.

Kanodia, Chandra, Robert Bushman, and John Dickhaut. 1989. "Escalation Errors and the Sunk Cost Effect: An Explanation Based on Reputation and Information Asymmetries." *Journal of Accounting Research*, 27(1): 59–77.

McAfee, R. Preston, Hugo M. Mialon, and Sue H. Mialon. 2010. "Do Sunk Costs Matter?" *Economic Inquiry*, 48(2): 323–36.

Milgrom, Paul, and Chris Shannon. 1994. "Monotone Comparative Statics." *Econometrica*, 62(1): 157–80.

Offerman, Theo, and Jan Potters. 2006. "Does Auctioning of Entry Licences Induce Collusion? An Experimental Study." *Review of Economic Studies*, 73(3): 769–91.

Phillips, Owen R., Raymond C. Battalio, and Carl A. Kogut. 1991. "Sunk and Opportunity Costs in Valuation and Bidding." *Southern Economic Journal*, 58(1): 112–28.

Piccione, Michele, and Ariel Rubinstein. 1997. "On the Interpretation of Decision Problems with Imperfect Recall." *Games and Economic Behavior*, 20(1): 3–24.

Rayo, Luis, and Gary S. Becker. 2007. "Evolutionary Efficiency and Happiness." *Journal of Political Economy*, 115(2): 302–37.

Robson, Arthur J. 2001. "Why Would Nature Give Individuals Utility Functions?" *Journal of Political Economy*, 109(4): 900–914.

Robson, Arthur J., and Larry Samuelson. Forthcoming. "The Evolution of Decision and Experienced Utility." *Theoretical Economics*.

Samuelson, Larry, and Jeroen M. Swinkels. 2006. "Information, Evolution and Utility." *Theoretical Economics*, 1(1): 119–42.

Shank, John K., and Vijay Govindara. January 1989. *Strategic Cost Analysis: The Evolution from Managerial to Strategic Accounting*. Burr Ridge, IL: Irwin.

Shim, Eunsup. 1993. "Cost Management and Activity-Based Costing in a New Manufacturing Environment." PhD diss. Rutgers University.

Shim, Eunsup, and Ephraim F. Sudit. 1995. "How Manufacturers Price Products." *Management Accounting*, 76(8): 37–39.

Wilson, Andrea. 2003. "Bounded Memory and Biases in Information Processing." *NAJ Economics*, 5: Article 3.