On Prejudice

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Abstract

This paper examines how prejudice biases an evaluation outcome. We also show that referring to past data, which leads to prejudice, can give a better estimator for the quality of the object under evaluation, even if biased, in the sense that it reduces the mean squared error. However, in cases where the evaluation quality depends on the referee's effort as well as his ability, prejudice aggravates the evaluation outcome by dampening his refereeing efforts, thus possibly yielding a worse estimator than no prejudice even in terms of the mean squared error. If evaluators possess prejudice, a person's performance in the earlier stage of his career becomes more important, at least in the short run, thus creating an incentive to work harder in his earlier stage than in the later stage. This may provide an alternative explanation for cutthroat competition in the earlier stage to the traditional signaling argument.

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1 Introduction

"The superior man does not promote a man simply on account of his words, nor does not he put aside good words because of man." Confucian Analects, Book XV (Wei Ling Kung), Chapter XXII

One makes numerous choices during his/her lifetime: Which stock should I purchase? Whom should I make friends with? Should I go to college or get a job? Which college should I attend? What job should I pursue? Whom should I marry? Making choices among a set of alternatives is the reality itself that everyone who does not have unlimited resources at their disposal must face. In order to make a choice, however, one must be able to evaluate the value of the alternatives prior to the forging of the actual decision. The evaluation represents an essential procedure that must be carried out before a rational choice can be made.

The value of an evaluation depends crucially on its objectiveness. However, evaluations tend to be subjective in many instances and are affected by predisposed perceptions about the object under evaluation, so-called prejudice. Evaluators are prone to utilize any additional external information pertaining to the value of the object under scrutiny that is available, in order to forge a more precise evaluation or to save the evaluation cost. But prejudice may be formed during this process of seeking external information. Prejudice can come from various sources. An evaluator may judge the quality of an article submitted to a journal based on the author's affiliation, race, gender or even on the software program with which the article was written, or most importantly, on the author's past record. There is a high likelihood that a referee's evaluation of an article conducted prior to his gaining knowledge about the author will be significantly different from the one he would conduct after having acquired such knowledge. This may simply be because he cannot be 100% sure of the quality of his evaluation. Therefore, he may think that the article may have some merits that he overlooked, and thus may prefer to have recourse to the market's evaluation in order to identify any components which might be missing. This may be one major source of his prejudice. A similar pattern unfolds with regards to a committee's collective decision-making process. If past proposals made by a committee member have proved to be of little actual value, his proposal will not be taken seriously by other members no matter how alluring it might appear.

Another important criterion for good evaluation besides objectivity is accuracy. Thus the meaning of good evaluation should be flexible, depending on the prevailing situation. While in some cases fairness (or objectiveness) may need to be focused on more, in other cases efficiency (or accuracy) may be the primordial factor. An unfair decision may cause great turmoil when the issue at stake is a politically subtle one. Alternatively, if the safety of numerous people depends crucially on the project under consideration, as is the case with the construction of nuclear power plants, evaluations should be done as accurately as possible to minimize the expected social losses incurred as a result of the failure of the project. When fairness is deemed to be a more crucial criterion than accuracy, the evaluator should make every effort to minimize the bias of his evaluation. However, when accuracy is the priority, he should focus on minimizing a suitably defined error function, for example, the mean squared error. Therefore, depending on the context, the prejudice formed from relying on other characteristics not directly related to the value of an object may actually have a positive effect on the evaluation outcome.

In this paper, we will define prejudice, i.e., objectify the subjectiveness, and show how an evaluation outcome can be biased when the evaluator is prejudiced. Roughly, we will say that an evaluator exhibits prejudice in evaluating an object if he resorts to other sources than the object itself, sources which might be remotely or not even related to the value of the object. More specifically, in a setup in which research outputs produced by a scholar at each period are to be evaluated, we consider the prejudice of an evaluator as a form of the weighted sum of his current evaluation and of the market evaluation for past performances. We will demonstrate that such prejudice leads to a biased evaluation.

In Section 3, we show that if prejudice is formed in such a manner, it may generate a better estimator of the quality of the object under evaluation in terms of the mean squared error, provided that the weight is appropriately chosen, although it is very difficult in a practical sense to find the appropriate value of the weight. In fact, even though they are aware of the possibility of generating a bias in their evaluation, most evaluators desire to learn more about the author of the paper under review in order to forge a better evaluation of the paper in question. Intuitively, this is because relying on additional information may increase the precision of the evaluation. Specifically, knowledge about the identity of the author gives a signal for his ability, which in turn can provide additional information about the quality of his current paper. Thus, referring to past data in this way can be understood as a natural process to make a better evaluation of the paper by abandoning unbiasedness. Also, we confirm the popular belief that the tendency to rely on the market evaluation of previous works appears to be stronger amongst those referees with poorer evaluation ability.

In Section 4, we consider a situation in which each referee can choose an unobservable effort level instead of assuming an exogenous effort level. We show that in this situation, prejudice aggravates the evaluation outcome by dampening refereeing efforts, thus possibly yielding a worse estimator than no prejudice even in terms of the mean squared error.

The momentum due to prejudice makes one-time overestimation (or underestimation) pervasive. This leads us to suspect that a person's ability could be overestimated (or underestimated) perpetually with positive probability as a result of overestimation (or underestimation) of his initial output. However, this turns out not to be the case. It is demonstrated that a person's true ability is learned in the long run with probability one in the presence of prejudice.

It is undeniable that if prejudice comes into play at all during the evaluation process, a person's performance in the earlier stage of his career becomes more important at least in the short run. Therefore, if his performance is determined not only by his ability but also by his own efforts, prejudice induces a person to work harder in his earlier stage than in the later stage in order to be highly appraised. This may provide an alternative explanation (to the traditional signaling arguments by Spence (1973) and Akerlof (1976)) for cutthroat competition among high school students (in Far Eastern countries such as Korea, Japan) or among first-year graduate students. Section 5 contains this discussion.

The existing literature on career concerns (e.g., Fama [1980], Meyer [1992], Prendergast and Stole [1996], Holmström [1999]) share much in common with this paper. For example, Holmström (1999) also considers a model in which the (per period) performance of an agent (a manager) is stochastically determined by his effort level in each period as well as his ability, and his wage is determined by his past performances. His model corresponds to the case of prejudice in our model, in the sense that his past performances affect his current wage level in a manner that is similar to how an author's past performances affects the evaluation of his current paper. As such, it is not surprising that similar results are obtained; the equilibrium sequence of the agent's effort levels is declining and the true ability of the agent becomes fully known eventually. The insight is that an agent works harder in earlier periods (when his ability is little known) in order to look more capable, while having no incentive to work hard in the limit since his ability is ultimately fully known. Although his insight is similar to ours, there are some important differences. In his model, the market is not fooled by the agent's overwork in his earlier periods because it can infer equilibrium effort levels and adjust his performances accordingly. In our model, the market (referees) cannot infer an author's effort level as long as his ability is not known. In Holmström, too, the market does not know his ability in the beginning, but the current wage level is determined by the expectation of his current performance, not by his current performance itself. So, by taking expectations, the market can infer an agent's effort without knowing the true value of his ability. Also, unlike his model, an author has an incentive to work in the limit in our model because what the author cares about is the evaluation of each period's output, not the evaluation of his ability itself.[1] Meyer (1992) shows that in a two-period tournament it is optimal to bias the second contest in favor of the first-period winner. In our model, the evaluation bias is not formed from a consideration of providing authors an incentive to work harder, which is the main difference from her insight.

The argument developed in this paper can be directly applied to other types of prejudice, including statistical discrimination on the basis of the author's affiliation or sex. This paper predicts that an evaluation of the quality of an article by taking into account external characteristics of the author as noisy signals leads to bias in the evaluation of the article; however, the bias from such prejudice will erode away in the long run when there is no inherent difference among groups with different characteristics in terms of their productivity.

It deserves comparing our model with existing literature on statistical discrimination. Two pioneering works in the theory of statistical discrimination are by Arrow (1973), and by Phelps (1972). Theories of statistical discrimination are built on imperfectness of observable signals about unobservable productivity of workers. Arrow showed that unequal outcomes in the labor market can be caused by an employer's asymmetric belief about productivity of workers among groups which is self-fulfilling. Phelps attributes statistical discrimination to different variances in inferred productivity, instead of an employer's asymmetric belief.

[1] In most of the literature on career concerns (for example, Trueman [1994], Prendergast and Stole [1996]), an agent is assumed to care about the evaluation of his ability.

Although our model is close in spirit to their models and those subsequent to them,[2] there are crucial differences. First, whereas, in theories of statistical discrimination, just as in most literature on career concerns, the interest of an employer is in assessing a worker's productivity, in our model, what is being evaluated is not a person's productivity, but the value of the outputs realized as a noisy signal of the productivity at each period. In our model, the past data of a person is of course directly related to the value of his productivity, but only indirectly related to the value of his output produced each period. Second, in the literature on statistical discrimination, the employer's assessment of workers' productivity is accurate in equilibrium in terms of expected value given his information, although he evaluates it based on the group identity which is irrelevant to a worker's productivity. That is, no economic discrimination occurs in statistical discrimination. In our model in which the value of outputs is evaluated, bias does occur, as long as the evaluator relies on the past data of a person. Third, in Arrow's model, an employer's asymmetric belief can lead to a long-run bias against a certain group whose average ability is inherently not different from that of other groups, whereas it cannot happen in our model.

This paper is also related to literature on cognitive dissonance and the first impression effect. Cognitive dissonance theory, on which much in psychology is based, argues that a person feels uncomfortable when maintaining two seemingly contradictory pieces of information.[3] Many economists have discussed the effect of cognitive dissonance on the market outcome. (See Akerlof and Dickens (1982), Gilad, Kaish and Loeb (1986), Rabin (1992).) Similarly, Rabin and Schrag (1999) discuss the effect of the first impression in making decisions. To incorporate cognitive dissonance into a rational choice framework, they distinguish perceived signals from true signals, and show that, contrary to the view of Bayesian statisticians, the first impression matters because there is a positive likelihood that a decision maker misinterprets signals that conflict with his current belief. Our approach is different from theirs, in the sense that we do not depart from Bayesian decision making and explain why the first impression can matter even without assuming cognitive dissonance.

Prejudice has been defined in a variety of ways in the psychological literature, with most

[2]See, for example, Coate and Loury (1993) and Mailath, Samuelson and Shaked (2000).

[3]See Festinger (1957).

of these definitions carrying a negative nuance.[4] Recently, however, it has been argued that there may be some fundamental problems with the idea of prejudice as a pejorative concept. Consequently, the idea that prejudice should necessarily be defined as 'bad' in some way has been seriously questioned. (Duckitt (1992)) One of the arguments is that no objective basis for the idea of prejudice as 'bad' has been provided, but the negative concept is due to an essentially subjective value judgment. In this paper, we partly share this view. In our definition of prejudice, no subjective value judgment is inherent. This paper only provides a theoretical framework within which a positive analysis can be made, and from which subjective value judgment can be drawn.

2 Model of Evaluation

An economic agent with ability θ performs an activity yielding an output, say writing an academic article, at each period $t = 1, 2, \cdots, \infty$. Denoting the true value of the t-period output by v_t, we assume that $v_t = \theta + \epsilon_t$ where ϵ_t is distributed with its mean 0 and its variance $\sigma_\epsilon^2 (< \infty)$. At each period t, N referees randomly chosen from a large population evaluate the output produced at the period i.e. estimate v_t. There may be two different ways of evaluating outputs over time. One involves anonymously distributing a paper to the referees (double-blindness) and the other giving out a paper without hiding the identity of the author (single-blindness).

Let referee i's evaluation on the t-period output when he reviews the paper with anonymity be m_{ti}. We assume that $m_{ti} = v_t + \eta_{ti}$ where θ, $\{\epsilon_t\}$, $\{\eta_{ti}\}$ are independent for all t, for all i, $E(\eta_{ti}) = 0$ and $\mathrm{Var}(\eta_{ti}) = \sigma_{\eta_i}^2 (< \infty)$. Throughout the paper, it will be assumed that σ_ϵ^2 and $\sigma_{\eta_i}^2$ are all known. The market evaluation of v_t is formed out of m_{ti}s. The market value for the t-th article can be viewed as a weighted average of N evaluations i.e., $m_t(N) = \sum_{i=1}^N \frac{m_{ti}}{\sigma_{\eta_i}^2} / \sum_{i=1}^N \frac{1}{\sigma_{\eta_i}^2}$.[5] We will omit N in $m_t(N)$ if there is no possibility of confusion.

We will define referee i as having prejudice if his overall evaluation is affected by other

[4]See, for example, Allport (1954) and Klineberg (1968).

[5]In reality, $m_t(N) = \sum_{i=1}^N m_{ti}/N$ is used as a proxy for the market value, since it is hard to know who were the referees either in single-blind refereeing or in double-blinnd refereing.

considerations (most importantly, the author's past record) than his own evaluation. Specifically, we consider a referee evaluating the second article after m_1 is determined, according to

$$\hat{m}_{2i} = \alpha_i m_{2i} + (1-\alpha_i)m_1, \tag{1}$$

where $m_1 = \sum_{i=1}^{N} \lambda_i m_{1i}$ with $\sum_{i=1}^{N} \lambda_i = 1$.[6] Here, notice that $m_1 = v_1 + \sum_{i=1}^{N} \lambda_i \eta_{1i} = v_1 + \overline{\eta}_1$ with $E(\overline{\eta}_1) = 0$ and $\mathrm{Var}(\overline{\eta}_1) = \sum_{i=1}^{N} \lambda_i^2 \sigma_{\eta_i}^2 \equiv \sigma_{\overline{\eta}}^2$.

3 Analysis

Since the refereeing mode can make no difference in the first-period evaluation, let us start our analysis by considering the second-period evaluation. Suppose v_2 is realized. It is obvious that m_{2i} is an unbiased estimator of v_2 in the sense that $E(m_{2i} \mid v_2) = v_2$. However, we can easily see that $\hat{m}_{2i}$ is a biased estimator of given v_2 in the sense that $E(\hat{m}_{2i} \mid v_1, v_2) \neq v_2$. To compute the bias, we have

$$\begin{aligned}
\text{bias} &= E(\hat{m}_{2i} - v_2 \mid v_1, v_2) \\
&= E[\alpha_i m_{2i} + (1-\alpha_i)m_1 - v_2 \mid v_1, v_2] \\
&= E[\alpha_i m_{2i} + (1-\alpha_i)m_1 - \alpha_i v_2 - (1-\alpha_i)v_2 \mid v_1, v_2] \\
&= (1-\alpha_i)E(m_1 - v_2 \mid v_1, v_2) \\
&= (1-\alpha_i)E(v_1 + \overline{\eta}_1 - v_2 \mid v_1, v_2) \\
&= (1-\alpha_i)(v_1 - v_2) \neq 0, \text{ if } v_1 \neq v_2.
\end{aligned}$$

This implies that evaluation tends to be biased, if it is made by taking into account the market evaluation for the author's past work.

However, it does not necessarily follow that m_{2i} is a better estimator of v_2 than $\hat{m}_{2i}$, because, depending on α_i, $\hat{m}_{2i}$ may have a smaller mean squared error (MSE), even if biased. We will examine this possibility by assuming that evaluators choose their weights before they start on the evaluation service.[7]

[6] This is quite a general formulation. It encompasses both $\sum_{i=1}^{N} \frac{m_{ti}}{\sigma_{\eta_i}^2} / \sum_{i=1}^{N} \frac{1}{\sigma_{\eta_i}^2}$ and $\sum_{i=1}^{N} m_{ti}/N$.

[7] This evaluation method is consistent with the Bayesian way of thinking (updating the belief as new information is available) since $\hat{m}_{2i}$ is a weighted average of m_{2i} and m_1 (new information). Due to the

Let us compute the MSE's of m_{2i} and $\hat{m}_{2i}$.[8] We have

$$\mathrm{MSE}(m_{2i}) = E(m_{2i} - v_2)^2 = E(\eta_{2i}^2) = \sigma_{\eta_i}^2,$$

$$\begin{aligned}
\mathrm{MSE}(\hat{m}_{2i}; \alpha_i) &= E(\hat{m}_{2i} - v_2)^2 \\
&= E[\alpha_i m_{2i} + (1-\alpha_i) m_1 - v_2]^2 \\
&= E[\alpha_i(\theta + \epsilon_2 + \eta_{2i}) + (1-\alpha_i)(\theta + \epsilon_1 + \overline{\eta}_1) - (\theta + \epsilon_2)]^2 \\
&= E[-(1-\alpha_i)\epsilon_2 + (1-\alpha_i)\epsilon_1 + \alpha_i \eta_{2i} + (1-\alpha_i)\overline{\eta}_1]^2 \\
&= 2(1-\alpha_i)^2 \sigma_\epsilon^2 + \alpha_i^2 \sigma_{\eta_i}^2 + (1-\alpha_i)^2 \sigma_{\overline{\eta}}^2.
\end{aligned}$$

The difference yields

$$\begin{aligned}
\phi(\alpha_i) \equiv \mathrm{MSE}(\hat{m}_{2i}; \alpha_i) - \mathrm{MSE}(m_{2i}) &= 2(1-\alpha_i)^2 \sigma_\epsilon^2 + \alpha_i \sigma_{\eta_i}^2 + (1-\alpha_i)\sigma_{\overline{\eta}}^2 - \sigma_{\eta_i}^2 \\
&= \alpha_i^2 (2\sigma_\epsilon^2 - \sigma_{\eta_i}^2 + \sigma_{\overline{\eta}}^2) + 2\alpha_i(2\sigma_\epsilon^2 + \sigma_{\overline{\eta}}^2) + 2\sigma_\epsilon^2 - \sigma_{\overline{\eta}}^2 - \sigma_{\eta_i}^2 \\
&= (2\sigma_\epsilon^2 + \sigma_{\eta_i}^2 + \sigma_{\overline{\eta}}^2)[\alpha_i - \frac{2\sigma_\epsilon^2 + \sigma_{\overline{\eta}}^2}{2\sigma_\epsilon^2 + \sigma_{\eta_i}^2 + \sigma_{\overline{\eta}}^2}]^2 - \frac{\sigma_{\eta_i}^4}{2\sigma_\epsilon^2 + \sigma_{\eta_i}^2 + \sigma_{\overline{\eta}}^2}.
\end{aligned}$$

Therefore, the minimum is attained at $\alpha_i^* = \frac{2\sigma_\epsilon^2 + \sigma_{\overline{\eta}}^2}{2\sigma_\epsilon^2 + \sigma_{\eta_i}^2 + \sigma_{\overline{\eta}}^2} \in [0,1]$ and the minimum difference is $\phi(\alpha_i^*) = -\frac{\sigma_{\eta_i}^4}{2\sigma_\epsilon^2 + \sigma_{\eta_i}^2 + \sigma_{\overline{\eta}}^2} < 0$. This implies that m_{2i}, in general, does not minimize the MSE, although it is the most efficient linear unbiased estimator (BLUE) of v_2. By giving up the unbiasedness, one can get a better estimator of v_2 which has smaller MSE than m_{2i}. After all, without anonymity, a referee may evaluate a paper better although the evaluation may be biased. In reality, however, it seems very hard for a referee to compute the optimal value of α_i from noisy information about σ_ϵ^2, $\sigma_{\eta_i}^2$, $\sigma_{\overline{\eta}}^2$. This may be a reason why many academic journals insist on double-blind reviewing policy. To summarize, we have

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assumption that a population of referees is very large, the probability that a specific pair of a referee and an author is rematched soon is very low, so it can be an optimal decision for a Bayesian referee (one-shot player) to make a sincere evaluation unlike an editor (repeat player).

[8] Here, we are abusing the term "mean squared error" which is usually defined for an estimator of an unknown parameter. However, since α_i is chosen prior to period 1 in which v_2 is not realized yet, it is more relevant to treat v_2 as a random variable unlike in the case of computing the bias. So, MSEs we are computing are very close to the concept of "risk" used by Bayesian statisticians. It can be called more accurately the "expected squared distance between m and v".

Proposition 1 *(i)* $\alpha_i^* = \frac{2\sigma_\epsilon^2+\sigma_{\overline{\eta}}^2}{2\sigma_\epsilon^2+\sigma_{\eta_i}^2+\sigma_{\overline{\eta}}^2}$ *and (ii)* $MSE(\hat{m}_{2i};\alpha_i^*) < MSE(m_{2i})$.

Some comparative statics follow.

Proposition 2 *(i)* α_i^* *is strictly increasing in* σ_ϵ^2. *(ii)* α_i^* *is strictly decreasing in* $\sigma_{\eta_i}^2$.

Proof. This is direct from Proposition 1(i).

Implications of this proposition can be given as follows. First, as σ_ϵ^2 becomes larger, i.e., variation of the quality is larger, a referee must put more weights on his current evaluation. In one extreme, as σ_ϵ^2 goes to infinity, α_i^* approaches 1. Intuitively, if variation of the quality of an author's work is very large, the evaluator will have to ignore the past data and rely only on the current evaluation of his own. In the other extreme, as σ_ϵ^2 goes to zero, α_i^* approaches $\frac{\sigma_{\overline{\eta}}^2}{\sigma_{\eta_i}^2+\sigma_{\overline{\eta}^2}}$, not zero. If a person's performance is not varied over time, the market evaluation for his past work as well as the evaluator's own evaluation for the author's current work should be seriously taken into account to estimate v_2 and each weight on m_{2i} and m_1 must be inversely proportional to the relative size of $\sigma_{\eta_i}^2$ and $\sigma_{\overline{\eta}}^2$, specifically, approaches one half if $\sigma_{\eta_i}^2$ are the same for all i. Second, as $\sigma_{\eta_i}^2$ is smaller i.e. referee i is more able, he has to rely less on the market value of the author for evaluating a paper. This is intuitively clear. Relatedly, note that $\phi(\alpha_i^*)$ is strictly increasing in $\sigma_{\eta_i}^2$. This can be also explained by the intuition that a referee can estimate v_2 more accurately by utilizing the past market evaluation, as his evaluation ability is lower ($\sigma_{\eta_i}^2$ is larger).

General Properties In the case that evaluations are made on the basis of double-blindness so that referees do not hold prejudice, we can establish some straightforward results.

Proposition 3 *Suppose that* $\limsup_N \frac{N}{\sum_{i=1}^N \frac{1}{\sigma_{\eta_i}^2}} < \infty$ *and* $\sum_{i=1}^N \frac{1}{i^2}\frac{1}{\sigma_{\eta_i}^2} < \infty$. *(i) For given* v_t, $m_t(N)$ *is an unbiased and consistent estimator of* v_t *as* $N \to \infty$. *(ii)* $m(N)$ *is an unbiased and consistent estimator of* θ *for all* N *as* $t \to \infty$.

Proof. See the appendix.

Proposition 3-(i) says that the market value for the t-th paper, $m_t(N)$, converges to the true value v_t as the number of referees becomes larger, and Proposition 3-(ii) implies that one can use $m(N) \equiv \lim_{T\to\infty} \sum_{t=1}^{T} m_t(N)/T$ as a proxy for the ability of an agent. The assumptions in Proposition 3 are satisfied when referees have the same variance so that $\sigma_{\eta_i}^2 = \sigma_\eta^2$ or when the variances of referee's evaluation are bounded from below and above so that $a \leq \sigma_{\eta_i}^2 \leq b$ for some positive constant a and b.

On the other hand, suppose that the journal releases the information about the identity of the author, so that a referee can refer to the past performance of the author at each period. For simplicity, we assume that $\sigma_{\eta_i}^2 = \sigma_\eta^2$ for all i.

In general, evaluation on the t-th article can be made by

$$\hat{m}_{ti} = \alpha m_{ti} + (1-\alpha)\hat{m}_{t-1}, \tag{2}$$

where $\hat{m}_{t-1} = \sum_{i=1}^{N} \hat{m}_{(t-1)i}/N$. This implies that

$$\hat{m}_t = \alpha m_t + (1-\alpha)\hat{m}_{t-1}. \tag{3}$$

In principle, referee i can adjust α over time to minimize the mean squared error of $\hat{m}_{ti}$. However, it usually requires too much knowledge for a referee to choose the optimal α at each period, especially for a very large t. So, in this paper, we ignore the possibility and assume that α is constant over time.

We saw that $\hat{m}_t$ is, in general, a biased estimator of v_t. Other than that, we can see that one-time overestimation (or underestimation) of a person is quite pervasive if referees hold prejudice. To illustrate, suppose that $v_1 > \theta$ i.e., the author was lucky in the first period in the sense that the value of his first-period output was higher than his true ability. Then, for a very large N, we must have $m_1(N) > \theta$, since $\lim_{N\to\infty} m_1(N) = v_1 > \theta$. Now, suppose that $v_2 < \theta$ and that $v_1 - \theta = \theta - v_2$ i.e., he is unlucky in the second period just as much as he was lucky in the first period. Then, the evaluation on his ability at $t = 2$ is given by

$$\begin{aligned}
\frac{m_1 + \hat{m}_2}{2} &= \frac{m_1 + \alpha m_2 + (1-\alpha)m_1}{2} \\
&\approx \frac{(2-\alpha)v_1 + \alpha v_2}{2} \\
&= \frac{(2-\alpha)(b_1+\theta) + \alpha(b_2+\theta)}{2} \\
&= \theta + \frac{(1-\alpha)}{2} b_1 > \theta \text{ for a very large } N,
\end{aligned}$$

where $b_t = v_t - \theta$. This implies that, if an author was overestimated in the first period, he tends to be overestimated in the second period.

More generally, one can evaluate the ability of an author at period T by the average of the market performances up to T, i.e., $\frac{\sum_{t=1}^{T} \hat{m}_t}{T}$. If one adds (3) for all t up to T, we have

$$\sum_{t=1}^{T} \hat{m}_t = \sum_{t=1}^{T} \beta_t m_t, \tag{4}$$

where $\beta_1 = \sum_{\tau=1}^{T-1}(1-\alpha)^{\tau}$ and $\beta_t = \alpha \sum_{\tau=1}^{T-t}(1-\alpha)^{\tau}$, $2 \leq t \leq T$. Notice that $\beta_1 > \beta_2 > \cdots > \beta_T$. This means that the market evaluation of the first-period paper is most important in evaluating a person's ability. This suggests why and how the first impression is important in evaluation. It is because the first-period market evaluation for a person's work affects the evaluation for his work in subsequent periods if his identity is known to the referees.

One may wonder if the average of the market evaluations for a person's work formed by prejudice eventually biases his ability. The following proposition shows that it is not the case.

Proposition 4 *$\hat{m} = \theta$, where $\hat{m} = \lim_{T\to\infty} \frac{\sum_{t=1}^{T} \hat{m}_t}{T}$.*

Proof. See the appendix.

According to this proposition, prejudice may bias the evaluation for each paper, but the bias does not affect the evaluation for the person's ability in the long run. Intuitively, this is because the first impression effect gets wearing out and the biases will be averaged out for the whole life span. It deserves to be stressed, though, that the bias for a person' ability due to prejudiced evaluation will not be completely eliminated as long as he lives for finite periods.

4 Evaluation with Endogenous Efforts of Referees

The accuracy of evaluation usually depends not only on a referee's evaluation ability, but also on his effort devoted to evaluation. The analysis so far implicitly assumed that each referee exerts a fixed identical effort level. This could be justified if effort levels are observable. In this section, we consider a more realistic scenario. We assume that referees choose their effort levels optimally by taking refereeing costs into account. We will see how the results so far can be affected by the realistic ingredient.

We denote referee i's effort level by e_i and assume that $\sigma^2_{\eta_i} = s(e_i, \vartheta_i)$ where $\partial s/\partial e_i \equiv s_e < 0$, $\partial s/\partial \vartheta_i \equiv s_\vartheta < 0$, $s_{e\vartheta} < 0$, $s_{ee} > 0$ for all e, ϑ, i and $s_e(0, \vartheta_i) = -\infty$, $\lim_{e_i \to \infty} s_e(e_i, \vartheta_i) = 0$ for all ϑ, i. The first two assumptions imply that a lower variance (or a higher precision) is associated with higher refereeing effort and higher refereeing ability. The third assumption implies that greater effort increases the precision of a higher-ability referee more. All the rest are technical assumptions for ensuring the existence of the solution.

A referee wants to minimize his total cost which consists of his direct cost of making efforts and his indirect cost from a loss in reputation due to wrong evaluation that can be measured by MSE,

$$C = \text{MSE} + \gamma e_i,$$

where γ is a scaling parameter and can be interpreted as a unit cost of effort.

As a benchmark case, first consider the case of no prejudice. A referee i will choose his effort to

$$\min_{e_i} C(e_i, \vartheta_i) = \text{Var}(m_{2i}; e_i, \vartheta_i) + \gamma e_i.$$

The first-order condition requires that

$$\frac{\partial C}{\partial e_i} = s_e(e_i; \vartheta_i) + \gamma + \gamma = 0. \tag{5}$$

This has the usual interpretation that the marginal reputational benefit from an increase in effort $(-s_e)$ equals the marginal cost of greater effort (γ). From this, we obtain the optimal refereeing effort $e_i^* = e^*(\vartheta_i)$. Note that $de_i^*/d\vartheta > 0$. That is, a more able referee puts more efforts in refereeing, since his marginal productivity is higher than that of a less able referee.

On the other hand, with prejudice, a referee's objective is to choose both α_i and e_i to

$$\begin{aligned} \min_{\alpha_i, e_i} C(\alpha_i, e_i; \vartheta_i) &= \text{MSE}(\hat{m}_{2i}; \alpha_i, e_i, \vartheta_i) + \gamma e_i \\ &= (1-\alpha_i)^2(2\sigma^2_\epsilon + \sigma^2_{\overline{\eta}}) + \alpha_i^2 \sigma^2_{\eta_i} + \gamma e_i. \end{aligned} \tag{6}$$

Note that this is an N-person game since $\sigma^2_{\overline{\eta}}$ involves $(e_i)_{i=1}^N$. To make the problem tractable, we assume that $\vartheta_i = \vartheta$ for all i and focus only on a symmetric equilibrium. By suppressing subscript i and using $\sigma^2_{\overline{\eta}} = \sum_{i=1}^{2} \frac{\sigma^2_\eta}{N^2}$, (6) can be written as

$$\begin{aligned}
\min_{\alpha,e} C(\alpha, e; \vartheta) &= (1-\alpha)^2(2\sigma^2_\epsilon + \sigma^2_{\overline{\eta}}) + \alpha^2\sigma^2_\eta + \gamma e \\
&= 2(1-\alpha)^2\sigma^2_\epsilon = \left(\frac{(1-\alpha)^2}{N} + \alpha^2\right)\sigma^2_\eta + \gamma e.
\end{aligned}$$

First-order conditions imply

$$\frac{\partial C}{\partial \alpha} = \alpha(2\sigma^2_\epsilon + \sigma^2_{\overline{\eta}} + \sigma^2_\eta) - (2\sigma^2_\epsilon + \sigma - \overline{\eta}^2) = 0, \tag{7}$$

$$\frac{\partial C}{\partial e} = \left(\frac{(1-\alpha^{**})^2}{N} + \alpha^{**2}\right) s_e(e^{**}, \vartheta) + \gamma = 0. \tag{8}$$

Proposition 5 $e^{**} < e^*$.

Proof. This is direct from $\frac{(1-\alpha^{**})^2}{N} + \alpha^{**2} < 1$.

Intuitively, under prejudice, a higher precision in evaluation obtained from an additional effort is not fully reflected in the final report of the referee, which makes him review less sincerely. This proposition has an interesting implication. It shows that single-blindness has another negative effect of dampening referee's efforts than creating a bias. If this effect is significant, the evaluation under single-blindness may be worse than the evaluation under double-blindness in terms of MSE as well as in terms of bias.

Let us illustrate this. For example, consider $\sigma^2_\eta = 1/e^2$. For values of $\sigma^2_\epsilon = 1$, $\gamma = 1$ and $N = 3$, we have $e^* = 1.2399$, $e^{**} = 1.0182$ and $\alpha^{**} = 0.7$, consequently $\mathrm{MSE}(\hat{m}_{2i}, \alpha^{**}, e^{**}) = .68144 > .62996 = \mathrm{Var}(e^*)$, while $C(\alpha^{**}, e^{**}) = 1.69964 < 1.88988 = C(e^*)$. In fact, it is easy to show that $C(\alpha^{**}, e^{**}) < C(e^*)$ for all γ, since $\max_\alpha C(\alpha, e) < C(e)$ for all e and for all γ.

This observation has an important implication on social welfare. If we define the social cost by C in the sense that it takes into account the referee's cost as well as the efficiency loss from evaluation errors,[9] it is clear that single-blindness is socially more desirable than double-blindness. However, the preference of a journal editor could be different. As long as his objective is to minimize the mean squared error, double-blindness may be preferred. Of

[9]Strictly speaking, the social cost should be defined by the average sum of the costs of N referees, but it does not matter at all since all of N referees have the same cost structure.

course, the definition of the social cost may be controversial, but we can say at least that if one takes the utility of referees into account, single-blindness is preferred because it can reduce referees' costs by inducing them to choose α optimally, while single-blindness can be worse as far as the quality and the reputation of the journal are concerned, because it can degrade the quality of evaluation by discouraging referees' efforts.

5 Evaluation for Action-Dependent Performances

In previous sections, we considered a model in which the quality of a paper was affected stochastically only by the author's ability. In this section, we will consider an extended model in which the quality of a paper depends not only on the author's ability but also on his effort.

Suppose that the true value of a paper written at period t is realized by $v_t = \theta a_t + \epsilon_t$. The author's per-period utility is assumed to be $u(m_t, a_t) = m_t - c(a_t)$ where $c' > 0$, $c'' > 0$. Let the discount factor be $\delta \in (0, 1)$. Then, the present discounted value of the total utility is given by $U = \sum_{t=1}^{\infty} \delta^{t-1} u(m_t, a_t)$. We assume that not only the current effort level but also all the past effort levels i.e. $a_1, \cdots, a_t$, are unobservable to referees at each period t.

No Prejudice

Suppose an author with ability θ writes an article with effort level $a_t(\theta)$ at period t. Then, we have $v_t = \theta a_t(\theta) + \epsilon_t$. Let the evaluation of referee i without prejudice be m_{ti} where $m_{ti} = v_t + \eta_i$. Here, we have $\lim_{N\to\infty} m_t(N) = v_t$. We assume that ϵ_t and η_i follow normal distributions.

Given that referees evaluate papers without prejudice, utility at each period is not affected by any state variable in previoius periods, so that maximizing the total utility is equivalent to maximizing the utility each period. In other words, at each period an author will choose

$$\max_{a_t} E[u(m_t, a_t)] = E[m_t] - c(a_t) = E[v_t] - c(a_t) = \theta a_t - c(a_t).$$

The first-order condition implies

$$\theta = c'(a_t^*), \ \forall t, \tag{9}$$

or equivalently, $a_t^*(\theta) = g(\theta)$ for all t, where $g(\cdot) = c'^{-1}(\cdot)$. That is, the author with ability θ makes the same level of effort $g(\theta)$ for each period. Also, it is easy to see that $\frac{da_t^*}{d\theta} > 0$, implying that a more capable author is a harder researcher, just as a more capable referee reviews a paper more seriously. Intuitively, this is because a more able author gets higher returns from an additional effort level.

We also have $\lim_{T\to\infty} \sum_{t=1}^{T} m_t/T = \theta g(\theta)$. This implies that $\lim_{T\to\infty} \sum_{t=1}^{T} m_t/T$ is an unbiased and consistent estimator of the labor-embodied ability, $\theta g(\theta)$. Accordingly, we have a consistent (not unbiased) estimator of θ.

Prejudice

On the other hand, suppose evaluators hold prejudice. Then, the optimization problem that a person faces at each period is

$$\begin{aligned} V(\hat{m}_{t-1}, \theta) &\equiv \max_{a_t} E_t[\sum_{\tau=t}^{\infty} \delta^{\tau-t}\{\hat{m}_\tau - c(a_\tau)\}] \\ &= \max_{a_t} E_t[\hat{m}_t] - c(a_t) + \delta E_t[V(\hat{m}_t, \theta)]. \end{aligned} \tag{10}$$

For $t \geq 2$, we have

$$V(\hat{m}_{t-1}, \theta) = \max_{a_t} \alpha E_t[m_t] + (1-\alpha)\hat{m}_{t-1} - c(a_t) + \delta E_t[V(\hat{m}_t, \theta; \hat{m}_{t-1})].$$

The first-order condition implies that

$$\alpha\theta + \delta \frac{dE[V(\hat{m}_t(\tilde{a}_t), \theta; \hat{m}_{t-1})]}{da_t} = c'(\tilde{a}_t), \tag{11}$$

where $\tilde{a}_t$ is the optimal choice with prejudice. For $t = 1$, the first-order condition implies that

$$\theta + \delta \frac{dE[V(m_1(\tilde{a}_1), \theta)]}{da_1} = c'(\tilde{a}_1). \tag{12}$$

Thus, we have

Proposition 6 *(i) For all $t(\geq 2)$, $\tilde{a}_t(\hat{m}_{t-1})$ is the same if $\hat{m}_{t-1} = m$. (ii) $\tilde{a}_1 > a_1^*$.*

Proof. (i) This is immediate from the stationarity of V given that $\hat{m}_{t-1} = m$ for all $t \geq 2$. (ii) This is directly due to $\frac{dE[V(m_1(\tilde{a}_1),\theta)]}{da_1} > 0$.[10]

[10] This is due to the fact that all the functional forms satisfy assumptions for Theorem 9.2 from Lucas and Stokey (1989). See the supplementary material for a more rigorous proof.

Proposition 6(i) says that an agent makes the same effort from the second period on as long as his reputation is constant. This does not imply that his effort level will remain the same thereafter, because his reputation $\hat{m}_{t-1}$, in fact, varies over time. Under prejudice, a higher effort in period $t \geq 2$ has a smaller effect of improving the current evaluation but an additional effect on future evaluations. Since the latter effect depends on the actual realization of m_t, the relative size of $\tilde{a}_t$ and a_t^* is ambiguous except for $t = 1$. Proposition 6(ii) says that an agent works harder in the first period when evaluators are subject to prejudice than when they are not. Intuitively, this is because an additional effort in the first period increases his utility more through increasing the utility in the subsequent periods in expected terms.

To sum up, if the first impression matters due to the possible prejudice of referees in evaluation, an economic agent tends to overwork in the earlier stage of his career in order to take advantage of the prejudice. Contrary to the signaling argument that an agent overworks to reveal his unobservable ability indirectly through his observable effort level, this initial effect can occur even if the agent's action is not observable, so long as his outputs are observable. Considering the reality that an agent's effort is not always observable to others, this explanation may complement the signaling argument.

6 Discussion

In this section, we will discuss the effect of the changes in the underlying assumptions in order to elicit richer implications from our model.

A. Varying Difficulty in Evaluation

Difficulty in evaluation may vary from output to output. Let $\sigma_{\eta t}^2$ be the evaluation difficulty of the t-period output. Then, as an output at period t is harder to evaluate i.e. $\sigma_{\eta t}^2$ is larger, it will be optimal for referees to rely more on the past market value, since m_t is not so reliable information. Also, this may suggest that sticking to the single-blind reviewing policy is a good strategy for a journal specialized in fields in which it is relatively difficult to evaluate outputs with reasonable precision.

B. Cost of Keeping Anonymity

Keeping information anonymous often incurs some cost. Due to this administrative cost, anonymity is in many instances dispensed with, to the extent to which the bias coming from prejudice is not so serious. In qualifying examinations in graduate schools, anonymity is required since, due to its one-time nature, aftermath of the bias is expected to be serious. In course examinations, anonymity is usually not maintained. Also, this constitutes one of the main arguments for the single-blind reviewing policy.

C. People who Care About their Reputation

In section 5, we assumed that an agent's per-period utility depends on the market evaluation for the quality of his paper and showed that the agent will work harder in the first period in the presence of prejudice than in the absence of prejudice. If instead his utility depends directly on the evaluation for his own ability, he will have a stronger incentive to work hard in the first period in both cases, since the t-period reputation for his ability is affected by evaluation for the first-period paper more cumulatively through $\hat{m}_2$, $\hat{m}_3$, $\cdots$, as appearing in equation (4).

D. Remedy for the Moral Hazard of Evaluators

In Section 4, we discussed the moral hazard problem that appears when the evaluation precision of a referee is dependent on his efforts as well as his ability, and argued that single-blindness aggravates the problem. This problem is severe, especially when referees do not strongly believe that having a good relationship with the editor is very important for them. To alleviate the moral hazard problem, it is sometimes mandated that the evaluator is identified. A similar example is found in security funds in which the name of the fund manager is made available.

E. Journal Reputation

We assumed that referees are all selected from the same pool regardless of the journal policy, but a selection bias associated with the policy may occur. A journal's good reputation requires the high accuracy of evaluations. Thus, to maintain a good reputation, it is essential that the papers submitted be reviewed by capable referees. Referees will accept the task only when the (monetary or non-monetary) price paid by the editor exceeds the refereeing cost. Since, as we saw in Section 4, the total cost for a referee is smaller under single-blindness, the editor of a reputable journal may have to stick to a policy of single-blindness in order to recruit capable referees whose opportunity costs are relatively high.

F. Alternative Criterion to the Mean Squared Error

In this paper, we used the mean squared error of an evaluation as a proxy of its accuracy. In the particular context of academic journals, it may be as much important as the mean squared error to minimize the type I error, say, $\text{Prob}(m_{ti} \geq m \mid v_t < m)$ for some m which can be interpreted as the cutoff value for accepting a paper.[11]

Can we say that the evaluation under prejudice always yields a smaller type I error? The answer is a slightly modified "yes". In other words, under normal distributions of η_{ti}, it can be demonstrated that $P(\hat{m}_{2i} \geq m \mid v_2 < m) < P(m_{2i} \geq m \mid v_2 < m)$ for any m such that $m \geq m_0$ for some large m_0.[12] Intuitively, this is because $\text{Var}(\hat{m}_{2i}) < \text{Var}(m_{2i})$ so that the probability of such a tail event must be smaller under prejudice.

G. Limited Observability of the Past Evaluation

While in many instances referees can observe all the past evaluations of an agent,[13] they may not be able to observe all in some instances. The case of academic journals is a typical example. All that referees know is the acceptance/rejection decision,[14] not raw evaluation scores. In this case, a referee with prejudice may use different values of α, depending on

[11]We are grateful to an anonymous referee for suggesting this alternative measure.

[12]The proof is provided in the supplementary material.

[13]For example, a superior in an organization can observe internal evaluation scores of his subordinates. A patent officer can have access to all the past raw data for each application of a person. Judges can also refer to all the past litigation records of legal disputes. Here, the first example is distinguished from the others in the sense that the superior's objective is to evaluate the ability of his subordinate, not his performance in each period.

[14]It is usually not observed but may be inferred that a paper was rejected in the previous period.

whether or not an author successfully published in the previous period. If the author's paper was published in the first period, a referee may want to minimize the mean squared error of $\hat{m}_{2i} = \alpha m_{2i} + (1 - \alpha)m_1^*$ where m_1^* is an estimator of $E(m_1 \mid m_1 \geq m)$ for some known cutoff value m. If m is very high, the previous publication will give very precise information about m_1 and thus the mean squared error is expected to be reduced. On the other hand, the mean squared error given the previous rejection could be larger than without prejudice.

7 Implications and Concluding remarks

Many believe that knowledge of an author has some effect on the evaluation of his work by referees. This has been a subtle issue among scholars and editors in almost every field, including economics. This debate has naturally lead to empirical work which has investigated the effect of single-blind versus double-blind reviewing by comparing actual differences in publication outcomes.[15] Contrary to the literature which has addressed this issue empirically, this paper offers a theoretical explanation for it, uncovering a new aspect for the single-blind reviewing policy, although it also casts doubt on the actual effect by mentioning the difficulty in finding out the right value of the weight put on the outside sources.

Our assertion that prejudice can have a positive consequence (we are not saying that it is always good, just that it can be) may sound paradoxical, but it may give some insights for widespread phenomena, including, as Cleary and Edwards (1960) argue, why affiliation to major universities facilitates the publication of articles in academic journals (so-called halo effect), or why statistical discrimination is often observed. Rather than regarding such discriminations due to prejudice simply as 'bad' because resultant biases distort human resources, one may understand them as a consequence of the rational behavior of rational players to minimize their loss from errors which arise during the evaluation process.

[15] A short list includes Crane (1967), Ferber and Teiman (1980), Blank (1991), etc. There are also some empirical studies suggesting that evaluation of academic articles may not be entirely objective. Cleary and Edwards (1960) showed that a large proportion of the articles published in scholarly journals are contributed by authors from major universities. Yotopoulos (1961) found that journals edited at a particular university had a tendency to publish a higher proportion of articles by authors at the same university. Earlier, extreme unequality in scientific productivity was observed by Lotka (1926). His observation known as the Lotka's law suggests that only 6 percent of authors produce half of all papers.

We also demonstrated that the bias in evaluation from prejudice tends to be cumulative. Thus, the first impression does matter, at least in the short run, in a world of prejudice. However, it may not matter so much in the long run, because ultimately full learning of an agent's ability occurs even in the presence of prejudice.

Appendix

Proof of Proposition 3: (i) Unbiasedness is obvious from $E(\eta_{ti}) = 0$. $m_t(N)$ can be written as

$$m_t(N) = \left(\frac{N}{\sum_{i=1}^{N} \frac{1}{\sigma_{\eta_i}^2}} \right) \cdot \left(\frac{1}{N} \sum_{i=1}^{N} \frac{m_{ti}}{\sigma_{\eta_i}^2} \right),$$

and convergence of $\frac{1}{N} \sum_{i=1}^{N} \frac{m_{ti}}{\sigma_{\eta_i}^2}$ follows from the Kolmogorov's law of large numbers. (See, for example, Lemma 12.8 of Williams (1991).) (ii) Unbiasedness is obvious from $E(\epsilon_t) = E(\eta_{ti}) = 0$, and consistency follows from the Kolmogorov's law of large numbers.

Proof of Proposition 4: Recursive substitution in (3) yields

$$\sum_{t=1}^{T} \hat{m}_t = \alpha \sum_{t=1}^{T} m_t + (1-\alpha) \sum_{t=1}^{T-1} \hat{m}_t + (1-\alpha) m_1. \tag{13}$$

Let $\lim_{T\to\infty} \frac{\sum_{t=1}^{T} \hat{m}_t}{T} = M$ and suppose $|M| < \infty$. From equation (9), we have $M = \alpha\theta + (1-\alpha)M$, since $\lim_{T\to\infty} \frac{\sum_{t=1}^{T} m_t}{T} = \theta$. Thus, it follows that $M = \theta$.

It remains to show that $|M| < \infty$. Equation (4) can be rewritten as

$$\frac{\sum_{t=1}^{T} \hat{m}_t}{T} = \frac{1}{T} \frac{1-(1-\alpha)^T}{\alpha} m_1 + B,$$

where $B = \frac{1}{T} \sum_{t=2}^{T} [1-(1-\alpha)^{T-t+1}] m_t$. We have $\lim_{T\to\infty} \frac{1}{T} \frac{1-(1-\alpha)^T}{\alpha} m_1 = 0$. Also, since $\{m_t\}$ is i.i.d. and $0 < 1-(1-\alpha)^{T-t+1} < 1$, B converges *a.s.* by the law of large number. Therefore, it follows that $|M| < \infty$.

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Supplementary Material For Referees

A. Rigorous Proof for the Claim in Footnote 10:

7.1 Program

We have

$$V(\hat{m}) = \max_a [E[\hat{m}'] - c(a) + \delta E[V(\hat{m}')]] \tag{14}$$

$$s.t. \quad \hat{m}' = \alpha\left[\theta a + \epsilon + \frac{1}{N}\sum \eta_i\right] + (1-\alpha)\hat{m} \tag{15}$$

We can simplify it by inserting the constraint (15) into the program (14).

$$V(\hat{m}) = \max_a \left\{ [\alpha\theta a + (1-\alpha)\hat{m}] - c(a) + \delta E[V\left(\alpha\left[\theta a + \epsilon + \frac{1}{N}\sum \eta_i\right] + (1-\alpha)\hat{m}\right)]\right\}$$

In the first-order condition,

$$\begin{aligned}
& \frac{d}{da} E\left[V\left(\alpha\left[\theta a + \epsilon + \frac{1}{N}\sum \eta_i\right] + (1-\alpha)\hat{m}\right)\right] \\
= \; & E\left[\frac{d}{da} V\left(\alpha\left[\theta a + \epsilon + \frac{1}{N}\sum \eta_i\right] + (1-\alpha)\hat{m}\right)\right] \\
= \; & E\left[\alpha\theta V'\left(\alpha\left[\theta a + \epsilon + \frac{1}{N}\sum \eta_i\right] + (1-\alpha)\hat{m}\right)\right] > 0 \\
\Leftrightarrow \; & E[V'(\cdot)] > 0
\end{aligned}$$

Therefore, if we can prove $V'(\cdot) > 0$, then it is done.

7.2 Proof for $V'(\cdot) > 0$

Define $u_n(\cdot)$ recursively as

$$\begin{aligned}
u_0(\hat{m}) &= 0 \\
u_n(\hat{m}) &= \max_a \{E[\hat{m}'] - c(a) + \delta E[u_{n-1}(\hat{m}')]\} \\
& s.t. \quad \hat{m}' = \alpha m + (1-\alpha)\hat{m}
\end{aligned}$$

Then $u_n(\cdot)$ converges to $V(\hat{m})$ by Theorem 9.2 of Lucas and Stokey (1989). Detailed proof will be illustrated in the next subsection.

It is easy to show that $u_n'(\cdot) > 0$ for $n \geq 1$. Since $u_n(\cdot)$ converges to $V(\cdot)$, we conclude $V'(\cdot) \geq 0$. Therefore, it is left to show that $V(\cdot) \neq 0$.

By the envelope theorem, we get

$$V'(\hat{m}) = (1-\alpha)\left[1 + \delta E V'(\hat{m}')\right] \tag{ET}$$

Now suppose that $V'(\hat{m}) = 0$ for some $\hat{m}$, then by [ET], we get

$$V'(\hat{m}) = (1-\alpha)\left[1 + \delta E V'(\hat{m}')\right] = 0$$

which implies that $EV'(\hat{m}') < 0$, which is a contradiction. Therefore, we have shown that $V'(\hat{m}) > 0$.

7.3 The proof of the convergence of $u_n(\cdot)$ to $V(\cdot)$

Our functional assumptions satisfy Assumption 9.1 and 9.2 (b) from Lucas and Stokey (1989). Therefore, if we can show the assumption of Theorem 9.2, then we can use Theorem 9.2 of Lucas and Stokey.

More specifically, the choice set of y is $\Gamma(x,z)$ in Lucas and Stokey, and the choice set in our model is $\Gamma(\hat{m}) = \{(\hat{m}', a) | \hat{m}' = \alpha[\theta a + \epsilon + 1/n \sum \eta_i] + (1-\alpha)\hat{m}\}$. Since the set is a straight line in two dimensional real space, it satisfies Assumption 9.1.

By the same reason, Assumption 9.2 (b) is also automatically satisfied. $F[\pi_{t-1}(z^{t-1}), \pi_t(z^t), z_t]$ in assumption 9.2 (b) is congruent to $E[\hat{m}'] - c(a)$, where $\pi_t(z^t)$ is congruent to $(\hat{m}', a)$. Our model does not satisfy assumption 9.2 (a), but it satisfies 9.2 (b). The essential reason is that the error terms follow normal distribution. Although $\hat{m}$ can be enormously large, the probability goes to zero much faster than $\hat{m}$ goes to infinity, which is a property of normal distribution. Therefore, the limit exists.

7.4 Reply to the referee's comment

- *What is Γ, h etc. on page 19?:* The following is a conversion table.

Lucas and Stokey	(x,z)	y	$F(x,y,z)$	$\Gamma(x,z)$	β
This paper	$\hat{m}$	$(\hat{m}', a)$	$\mathbf{E}[\hat{m}'] - c(a)$	$\Gamma(\hat{m})$	δ

- *There is no $u_n(\pi, s_0)$ in the statement of Theorem 9.2, so how can it apply?*: We missed one formula in the restatement of Lucas and Stokey. We add it now.

Below are restated the basic recursive model and Assumption 9.1 and 9.2 in Lucas and Stokey.

7.5 Restatement of Lucas and Stokey (1989)

$$v(s) = v(x,z) = \sup_{y \in \Gamma(x,z)} \left[F(x,y,z) + \beta \int v(y,z')Q(z,dz') \right] \tag{5}$$

Assumption 9.1 Γ *is nonempty-valued and the graph of* Γ *is* $(\mathcal{X} \times \mathcal{X} \times \mathcal{Z})$*-measurable. In addition,* Γ *has a measurable selection; that is, there exists a measurable function* $h : S \to X$ *such that* $h(s) \in \Gamma(s)$*, all* $s \in S$

Assumption 9.2 $F : A \to \mathbb{R}$ *is* A*-measurable, and either (a) or (b) holds.*

a. $F \geq 0$ *or* $F \leq 0$

b. For each $(x_0, z_0) = s_0 \in S$ *and each plan* $\pi \in \Pi(s_0)$

$$F[\pi_{t-1}(z^{t-1}), \pi_t(z^t), z_t] \text{ is } \mu^t(z_0, \cdot)\text{-integrable, } t = 1, 2, \ldots;$$

and the limit

$$F[x_0, \pi_0, z_0] + \lim_{n \to \infty} \sum_{t=1}^{n} \int_{Z^t} \beta^t F[\pi_{t-1}(z^{t-1}), \pi_t(z^t), z_t] \mu^t(z_0, dz^t)$$

exists (although it may be plus or minus infinity).

Now let us define $u_n(\cdot)$ as

$$\begin{aligned} u_0(\pi, s_0) &= F[x_0, \pi_0, z_0] \\ &\vdots \\ u_n(\pi, s_0) &= F[x_0, \pi_0, z_0] + \sum_{t=1}^{n} \int_{Z^t} \beta^t F[\pi_{t-1}(z^{t-1}), \pi_t(z^t), z_t] \mu^t(z_0, dz^r) \end{aligned}$$

Define the limit of $u_n(\cdot)$ by $u(\cdot)$.

$$u(\pi, s_0) = \lim_{n\to 0} u_n(\pi, s_0)$$

Theorem 9.2 *Let $(X, \mathcal{X}), (Z, \mathcal{Z}), Q, \Gamma,$ and β be given. Let Assumptions 9.1 and 9.2 hold, and let v^* be defined by $v^*(s) = \sup_{\pi\in\Pi(s)} u(\pi, s)$. Let v be a measurable function satisfying the functional equation (5) and such that*

$$\lim_{t\to\infty} \int_{Z^t} \beta^t v[\pi_{t-1}(z^{t-1}, z_t)]\mu^t(z_0, dz^t) = 0,$$
$$\text{all } \pi \in \Pi(s_0), all(x_0, z_0) = s_0 \in S$$

Let G be the correspondence defined the following

$$G(x, z) = \left\{ y \in \Gamma(x, z) : v(x, z) = F(x, y, z) + \beta \int v(y, z')Q(z, dz') \right\}$$

and suppose that G is nonempty and permits a measurable selection. Then $v = v^*$, and any plan π^* generated by G attains the supremum in $v^*(s) = \sup_{\pi\in\Pi(s)} u(\pi, s)$.

B. Comparison of Type I errors:

Since

$$\begin{aligned} m_{2i} &= v_2 + \eta_i, \quad \eta_i \sim N(0, \sigma^2_{\eta_i}), \\ \hat{m}_{2i} &= \alpha_i m_{2i} + (1-\alpha_i)m_1 \ = \ \alpha_i(v_2 + \eta_i) + (1-\alpha_i)(v_1 + \overline{\eta}_1), \end{aligned}$$

we obtain

$$\begin{aligned} \mathrm{Var}(m_{2i}|v_1, v_2) &= \sigma^2_{\eta_i}, \\ \mathrm{Var}(\hat{m}_{2i}|v_1, v_2) &= \alpha_i^2\sigma^2_{\eta_i} + (1-\alpha_i)^2\sigma^2_{\overline{\eta}}. \end{aligned}$$

When $\alpha_i = \dfrac{2\sigma^2_\epsilon + \sigma^2_{\overline{\eta}}}{2\sigma^2_\epsilon + \sigma^2_{\overline{\eta}} + \sigma^2_{\eta_i}}$, the difference can be computed as

$$\begin{aligned} \mathrm{Var}(m_{2i}|v_1, v_2) - \mathrm{Var}(\hat{m}_{2i}|v_1, v_2) &= (1-\alpha_i^2)\sigma^2_{\eta_i} - (1-\alpha_i)^2\sigma^2_{\overline{\eta}} \\ &= (1-\alpha_i)\left((1+\alpha_i)\sigma^2_{\eta_i} - (1-\alpha_i)\sigma^2_{\overline{\eta}}\right) \\ &= (1-\alpha_i)\left(\frac{(4\sigma^2_\epsilon + \sigma^2_{\overline{\eta}} + \sigma^2_{\eta_i})\sigma^2_{\eta_i})}{2\sigma^2_\epsilon + \sigma^2_{\overline{\eta}} + \sigma^2_{\eta_i}}\right) \ > 0. \end{aligned}$$

When $X \sim N(a, \sigma_1^2),\ Y \sim N(0, \sigma_2^2),\ \sigma_1^2 < \sigma_2^2$, we get

$$\begin{aligned} P(X > x) &= P(N(0,1) > \frac{x-a}{\sigma_1}), \\ P(Y > y) &= P(N(0,1) > \frac{x}{\sigma_2}). \end{aligned}$$

If $\frac{x-a}{\sigma_1} > \frac{x}{\sigma_2}$, i.e., $x > \frac{a/\sigma_1}{(1/\sigma_1 - 1/\sigma_2)}$, then $P(X > x) < P(Y > x)$. Using the above result, we know that

$$P(\hat{m}_{2i} > m | v_1, v_2) < P(m_{2i} > m | v_1, v_2)$$

for a sufficiently large m. Since the conditional variance does not depend on the value of v_1 and v_2, such m does not depend on v_1 and v_2. So the above inequality leads to

$$P(\hat{m}_{2i} > m | v_2 < m) < P(m_{2i} > m | v_2 < m)$$

for a sufficiently large m.