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Misspecification and Heterogeneity in Single-Index, Binary Choice Models

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Abstract: We propose a nonparametric approach for estimating single-index, binary-choice models when parametric models such as Probit and Logit are potentially misspecified. The new approach involves two steps: first, we estimate index coefficients using sliced inverse regression without specifying a parametric probability function *a priori*; second, we estimate the unknown probability function using kernel regression of the binary choice variable on the single index estimated in the first step. The estimated probability functions for different demographic groups indicate that the conventional dummy variable approach cannot fully capture heterogeneous effects across groups. Using both simulated and labor market data, we demonstrate the merits of this new approach in solving model misspecification and heterogeneity problems.

Keywords: Probit, Logit, Sliced Inverse Regression, categorical variables, treatment heterogeneity

JEL-Codes: C14, C21, C52

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1. Introduction

In this paper, we consider the problem of misspecified binary choice models and model heterogeneity associated with categorical explanatory variables. The leading examples of binary choice models, such as Probit and Logit, are single index models, i.e., $\Pr(y_i = 1 | x_i) = F(x_i' \beta)$, where the conditional probability function F is nonlinear in the single index $x_i' \beta$. The advantage of Probit and Logit specifications over a linear probability model is that the conditional probability function can be restricted to be between zero and one. However, there is no reason to believe that these parametric models necessarily capture the underlying nonlinear pattern in the data generating process. It is well-known that maximum likelihood estimates (MLE) of β are inconsistent if the parametric functional form of $F(x_i' \beta)$ is misspecified.

To consistently estimate index coefficients β , semiparametric methods have been proposed in the literature, including (1) maximum score estimator (Manski 1975, 1985), (2) smoothed maximum score estimator (Horowitz 1992), (3) maximum rank correlation estimator (Han 1987), (4) semiparametric MLE (Klein and Spady 1993), (5) semiparametric least squares (Ichimura 1993), and (6) derivative-based estimator (Powell, Stock, and Stocker 1989).

These semiparametric methods may avoid the model misspecification problem, but they also have technical problems and can be computationally difficult in practice. The first two estimators have convergence rates slower than root- n ; the third estimator is root- n consistent and asymptotically normal, but it requires that $F(x_i' \beta)$ be monotonically increasing in $x_i' \beta$. The fourth method estimates the index coefficients β by maximizing the log likelihood function

$$\sum_{i=1}^n \left[y_i \ln \hat{F}(x_i' \beta) + (1 - y_i) \ln (1 - \hat{F}(x_i' \beta)) \right],$$

where $\hat{F}(x'_i\beta)$ is a nonparametric estimate of $F(x'_i\beta)$ and n denotes the sample size. This estimate attains the semiparametric efficiency bound. But the procedure is time-consuming because it involves estimating $F(x'_i\beta)$ and searching for β iteratively. The fifth method is also not cheap to compute as it requires solving for $F(x'_i\beta)$ and $\partial F(x'_i\beta)/\partial x'_i\beta$ for all $i=1,\dots,n$. In addition, its asymptotic properties rely on the assumptions of asymptotic independence and stochastic equicontinuity, which impose restrictions on the nature of data. The last method estimates index coefficients using the density-weighted average derivatives of the regression function. This method is subject to the ‘*curse of dimensionality*’ because it is based on $\partial F(x'_i\beta)/\partial x_i$ and the advantage of the single-index restriction is essentially being lost. A detailed summary of semiparametric estimation of discrete choice models can be found in Pagan and Ullah (1999) and Cameron and Trivedi (2005). For applied researchers, these semiparametric methods are technically demanding and therefore, it is desirable to have a simple and efficient method for estimating single-index, binary-choice models.

We present a new two-step procedure for this purpose. In the first step, we estimate the single-index coefficients β using sliced inverse regression (SIR), a method originally proposed by Li (1991) for dimension reduction. In the second step, we estimate the conditional probability function $F(x'_i\beta)$ using kernel regression of the binary choice variable y_i on the estimated index $x'_i\hat{\beta}_{SIR}$, where $\hat{\beta}_{SIR}$ is obtained from the first step. To differentiate our method from parametric MLE and semiparametric methods, we call it a SIR-Nonparametric method.

In the first step, we favour SIR for four reasons. First, it assumes a multi-index model, which includes single-index, binary-choice models treated in this paper as a special case. Second, it imposes no parametric restrictions on the regression

function and the error term, thus avoiding model misspecification. Third, the SIR algorithm only requires estimating a covariance matrix and its eigen value decomposition, which is easy to implement and computationally fast. Fourth, the estimated index coefficients, $\hat{\beta}_{SIR}$, are root- n consistent, which in turn suggests that the estimated probability function $\hat{F}(x_i' \hat{\beta}_{SIR})$ in the second step converges to $F(x_i' \beta)$ at rate $n^{2/5}$ by the standard nonparametric regression results.

The two-step SIR-Nonparametric method (i.e., $\hat{\beta}_{SIR} \rightarrow \hat{F}$) has at least three comparative advantages. First, we do not estimate β in a traditional maximum likelihood framework whose consistency relies on correct model specification. Second, we do not need to estimate β and F iteratively (i.e., $\hat{\beta}_{MLE} \Leftrightarrow \hat{F}$) as Klein and Spady's semiparametric MLE (1993), which conserves computational time. Third, it allows us to include a large number of explanatory variables, unlike the derivative-based method of Powell, Stock, and Stocker (1989).

The second empirical modelling issue we tackle in this paper is how to handle categorical explanatory variables in binary choice models. The common practice is to combine categorical and continuous explanatory variables in a single index (e.g., Horowitz and Härdle 1996). This approach implicitly assumes that the conditional probability functions are identical across groups defined by categorical variables except for horizontal shifts. This assumption may be too strong and rarely satisfied in many empirical data sets.

An alternative approach is to treat categorical and continuous variables separately. Specifically, we construct sub-samples based on categorical explanatory variables. For each sub-sample, we allow for a different nonparametric model involving a dependent variable and continuous explanatory variables only. By so

doing, we can better capture heterogeneous relationships for different demographic groups or geographic regions.

We design four Monte Carlo experiments to show how SIR works compared to parametric MLE and to illustrate model heterogeneity. The first experiment shows that SIR outperforms Probit and Logit MLE when the data generating process is not governed by the Probit or Logit specification. The second experiment indicates that the efficiency loss of SIR to Probit MLE is trivial when the underlying true model is Probit. The third and fourth experiments demonstrate model heterogeneity associated with categorical variables. The results support the sub-sample estimation strategy and again favour SIR to Probit and Logit MLE.

We apply our SIR-Nonparametric method to a well-known dataset from the treatment evaluation literature. This literature lends itself to our approach because it commonly involves discrete-choice settings and a few categorical variables. Specifically, we re-examine the National Supported Work (NSW) Demonstration evaluation, previously studied by Lalonde (1986) and Dehejia and Wahba (1999). We stratify the data into eight demographic groups based on three categorical variables --- race, marital status, and a high-school degree indicator. For each group, we perform SIR and estimate a propensity score function nonparametrically. The estimated propensity score function has a different nonlinear pattern across the eight groups, which not only indicates that Probit and Logit models are misspecified but also supports our model heterogeneity argument. We then compute the average treatment effect on the treated (ATET) for each group using the nearest-neighbour matching method. The different values of ATET generated by SIR-Nonparametric method, Probit and Logit MLE suggest that the two modelling issues raised in this paper are not merely of theoretical interest but critically important for empirical analyses.

The rest of the paper is organized as follows. In Section 2, we discuss the possible sources of misspecification in binary choice models and motivate our nonparametric approach. Section 3 introduces the SIR theory and estimation algorithm. In Section 4, we compare SIR, Probit and Logit MLE in various settings via Monte Carlo simulations. In Section 5, we demonstrate our modelling strategy for treatment evaluation across heterogeneous demographic groups. Section 6 concludes the paper and suggests directions for future research.

2. Misspecification Problems

To understand the misspecification problems associated with Probit and Logit, we summarize the two models using the following three components: (i) an observable decision variable $y_i = 1[y_i^* > 0]$, where y_i^* is a continuous latent variable, $1[\cdot]$ is an indicator function that takes value one if $y_i^* > 0$ and zero if $y_i^* \leq 0$; (ii) a linear latent variable model $y_i^* = x_i'\beta + \varepsilon_i$, where x_i represents observed covariates and β is a column vector compatible with x_i ; (iii) the error term ε_i is independent of x_i . Assuming $\varepsilon_i \sim iid N(0,1)$ generates the Probit model, while $\varepsilon_i \sim iid$ standard logistic distribution generates the Logit model.

The conditional probability function of y_i given x_i is

$$(1) \quad p_i = \Pr(y_i = 1|x_i) = E(y_i|x_i) = F(x_i'\beta).$$

For the Probit model, $F(x_i'\beta) = \Phi(x_i'\beta)$, where $\Phi(\cdot)$ is the CDF of the standard normal distribution. For the Logit model, $F(x_i'\beta) = L(x_i'\beta) = \exp(x_i'\beta)/[1 + \exp(x_i'\beta)]$, where $L(\cdot)$ denotes the CDF of the standard logistic distribution. Maximum likelihood

estimates (MLE) of β are consistent when the functional form of $F(x_i'\beta)$ is correctly specified.

However, there are two possible sources of misspecification. First, the model for the latent variable y_i^* may not be linear in $x_i'\beta$. Second, the error term ε_i may not follow a standard normal or logistic distribution. If the linear latent variable model $y_i^* = x_i'\beta + \varepsilon_i$ is correctly specified, quasi-MLE of β is consistent as long as the specified density of ε_i belongs to the linear exponential family (e.g., Normal, Exponential, Bernoulli, Poisson). But y_i^* is unobservable, and therefore it is difficult to check any parametric restrictions imposed on it using empirical data. In this sense, all parametric binary choice models are potentially misspecified. A misspecified parametric model generates not only incorrect parameter estimates but also misleading probability predictions.

To solve this problem, we propose a more general framework as follows:

(i) $y_i = 1[y_i^* > 0]$; (ii) $y_i^* = H(x_i'\beta) + \varepsilon_i$, where $H(\cdot)$ is unknown; (iii) ε_i is independent of x_i . We can consistently estimate the index coefficients β using sliced inverse regression (Li 1991) without imposing parametric structure on $H(\cdot)$ and distributional assumption on ε_i . We will introduce the theory and estimation procedure of SIR in Section 3.

The second misspecification problem is the failure of modelling heterogeneity across demographic groups. Suppose that the observed x covariates comprises a set of continuous variables, denoted by \tilde{x} , and a categorical variable, denoted by x^D . For example, x^D could be a marital status dummy variable, with $x_i^D = 1/0$ if individual i is married/not married. The conditional probability function may be different across married and unmarried groups. There is no reason to presume that such difference can

be fully captured by a single dummy coefficient α in models like $F(\tilde{x}'\beta + \alpha x^D)$. In this model, the difference between the two groups is $F(\tilde{x}'\beta + \alpha) - F(\tilde{x}'\beta)$, where α represents a horizontal shift of the conditional probability function. This specification restricts the conditional probability function to have the same curvature for the two groups on the entire support of $\tilde{x}'\beta$, which may be too strong for many applications.¹

We relax this restriction by assuming different nonparametric models for the married and unmarried groups, i.e.,

$$(2) \quad p_{i1} = \Pr(y_i = 1 | \tilde{x}_i, x_i^D = 1) = E(y_i | \tilde{x}_i, x_i^D = 1) = F_1(\tilde{x}_i' \beta_1)$$

for the married group and

$$(3) \quad p_{i0} = \Pr(y_i = 1 | \tilde{x}_i, x_i^D = 0) = E(y_i | \tilde{x}_i, x_i^D = 0) = F_2(\tilde{x}_i' \beta_2)$$

for the unmarried group. Here, $F_1(\cdot)$ and $F_2(\cdot)$ can be different functions; β_1 and β_2 can be different vectors. If we have more than one categorical variable, we can split the sample into several strata and allow a different model for each stratum, i.e.,

$$(4) \quad p_{is} = \Pr(y_i = 1 | \tilde{x}_i, i \in s) = E(y_i | \tilde{x}_i, i \in s) = F_s(\tilde{x}_i' \beta_s),$$

where s represents the s^{th} stratum. This generalization enables us to better capture heterogeneous characteristics across different groups.

In summary, empirical data may have nonlinear conditional probability functions more complicated than those specified in Logit or Probit. This motivates estimating single-index coefficients using nonparametric methods that allow for general functional forms. In the next section, we suggest using sliced inverse regression (SIR) proposed by Li (1991) for this purpose. In addition, categorical

¹ In practice, this restriction can be relaxed by interacting the categorical variable(s) with other control variables to capture differences in response across categories. For example, in a Probit regression of employment, a marital status dummy interacted with years of schooling allows us to estimate differential effects of schooling across the different marital groups. Such specifications, while allowing more flexibility, do so within the framework of a parametric specification which is still potentially limiting.

variables may imply different nonlinear models for various demographic groups. Under such a circumstance, splitting data according to categorical variables may be necessary for obtaining consistent estimates of index coefficients. We demonstrate this point in Section 4 via Monte Carlo simulations.

3. Sliced Inverse Regression and Nonparametric Approach

In this section, we briefly introduce the fundamental theory of SIR and outline its estimation procedure. The inverse regression method assumes that the dependence relationship of y_i on the K -dimensional x_i is determined only through $J \leq K$ linear combinations of x_i , i.e.,

$$(5) \quad y_i = F(x_i' B, u_i),$$

where $B = [\beta_1 \cdots \beta_j \cdots \beta_J]$ is $K \times J$ and contains J column vectors known as “*effective dimension reduction*” (*e.d.r.*) directions. The regression function F is unknown, $x_i' B$ are called *inverse regression variates*, and u_i denotes an error term that is independent of x_i and has mean zero. The conditional probability function in (1) is a special case of (5), in which $J = 1$ (i.e., single index), y_i is a binary variable, and u_i is an additive error term.

Li (1991) proposes using sliced inverse regression of x_i on y_i to estimate B . For easy exposition, we standardize x_i to $z_i = \Sigma_X^{-1/2} [x_i - E(x_i)]$, where Σ_X denotes the $K \times K$ covariance matrix of x_i . Under a linear design condition (Li 1991, Condition 3.1), Li shows that the centred inverse regression curve $E(z_i | y_i)$ is contained in the linear subspace spanned by $\eta_j = \Sigma_X^{1/2} \beta_j \quad \forall j = 1, 2, \dots, J$ (Li 1991, Corollary 3.1). This result implies that the covariance matrix $Cov[E(z_i | y_i)]$ is

degenerate in any direction orthogonal to $\text{Span}[\eta_1 \cdots \eta_j \cdots \eta_J]$. Therefore, $[\eta_1 \cdots \eta_j \cdots \eta_J]$ are the eigenvectors associated with the J nonzero eigenvalues of $\text{Cov}[E(z_i | y_i)]$, and the *e.d.r.* directions are $[\beta_1 \cdots \beta_j \cdots \beta_J]$ with $\beta_j = \Sigma_X^{-1/2} \eta_j \forall j = 1, 2, \dots, J$.

The eigen decomposition of $\text{Cov}[E(z_i | y_i)]$ requires an estimate of $E(z_i | y_i)$. Li (1991) suggests using the mean values of z_i within several intervals or slices determined by y_i , which leads to the following SIR algorithm:

Step 1: Standardize x_i by an affine transformation to yield $\hat{z}_i = \hat{\Sigma}_X^{-1/2} [x_i - \bar{X}]$,

where $\hat{\Sigma}_X$ and \bar{X} are the sample covariance and mean of x_i , respectively.

Step 2: Divide the range of y_i into G slices, denoted by I_1, \dots, I_G . Let the proportion of the y_i 's that fall in slice g be w_g ($g = 1, 2, \dots, G$).

Step 3: Within each slice, compute the sample mean of \hat{z}_i , denoted by \hat{m}_g , such that the sliced mean $\hat{m}_g = (n w_g)^{-1} \sum_{y_i \in I_g} \hat{z}_i$.

Step 4: Calculate the weighted variance-covariance matrix of the sliced means $\hat{M}_{SIR} = \sum_{g=1}^G w_g \hat{m}_g \hat{m}_g'$, and then find its eigenvalues and eigenvectors.

Step 5: Let $\hat{\eta}_j$ ($j = 1, 2, \dots, J$) be the J largest eigenvectors of \hat{M}_{SIR} . The outputs, $\hat{\beta}_j = \hat{\Sigma}_X^{-1/2} \hat{\eta}_j$ ($j = 1, 2, \dots, J$), are the estimates of the *e.d.r.* directions.

Chen and Li (1998) show that $\hat{\beta}_j$ from SIR is root- n consistent and asymptotically normal with a covariance matrix that can be approximated by $n^{-1} \hat{\lambda}_j^{-1} (1 - \hat{\lambda}_j) \hat{\Sigma}_X^{-1}$, where $\hat{\lambda}_j$ is the j^{th} largest eigenvalue of the matrix \hat{M}_{SIR} in step 4.

The root- n consistency enables us to consistently estimate $F(x_i' \beta)$, the conditional

probability function defined in (1), nonparametrically by regressing y_i on $x_i' \hat{\beta}_{SIR}$. Nonparametric estimates have slower convergence rates than \sqrt{n} in general. Consequently, replacing the true β with its root- n consistent estimate does not affect the asymptotic properties of nonparametric estimates (see Chen and Smith 2008).

The remaining task is to determine J , the number of significant *e.d.r.* directions. To do so, we test the number of zero eigenvalues of \hat{M}_{SIR} . One can use the summation of the smallest $K - j$ eigenvalues of \hat{M}_{SIR} as the test statistic, i.e.,

$$(6) \quad \hat{\Lambda}_j = n \sum_{k=j+1}^K \hat{\lambda}_k,$$

where $\hat{\lambda}_1 \geq \dots \geq \hat{\lambda}_k \geq \dots \geq \hat{\lambda}_K$ and n is the sample size. Li (1991) derives the asymptotic distribution for the case where x_i is normally distributed. But in many applications, x_i may not be normally distributed.

To make inferences for general cases, Cook and Yin (2001, Section 3.3) develop the following permutation test. Let Θ be the $K \times K$ eigenvector matrix of \hat{M}_{SIR} . Partition $\Theta = [\Theta_1 \quad \Theta_2]$, where Θ_1 is $K \times j$ and Θ_2 is $K \times (K - j)$. The idea of the permutation test is that $x_i' \Theta_2$ should provide no information for y_i given $x_i' \Theta_1$ if $H_0: j = J$ is true. If we randomly permute $x_i' \Theta_2$ and recalculate $\hat{\Lambda}_j$ a large number of times, we can obtain a permutation distribution of $\hat{\Lambda}_j$. Comparing the $\hat{\Lambda}_j$ computed using the original data to its permutation distribution gives the p -value. Specifically, for testing $j = 0, 1, \dots$, we can use the following procedure:

Step 1: Compute $V_{1i} = x_i' \Theta_1$ and $V_{2i} = x_i' \Theta_2$.

Step 2: Randomly permute the indices i of $V_{2i} = x_i' \Theta_2$ to obtain a permuted set V_{2i}^* .

Step 3: Construct the test statistic $\hat{\Lambda}_j^*$ using the data (y_i, x_i^*) , where $x_i^* = [V_{1i} \quad V_{2i}^*]$.

Step 4: Repeat Steps 1-3 several times (e.g., 100 times) and save $\hat{\Lambda}_j^*$ each time.

Step 5: Compute the p -value, which is just the proportion of $\hat{\Lambda}_j^*$'s obtained in Step 4 that exceeds the $\hat{\Lambda}_j$ computed using the original data (y_i, x_i) .

We close this section with two remarks on the SIR algorithm and permutation test.²

Remark 1: If y_i is a binary variable, the maximum J obtained from SIR is one. Recall that SIR estimates $Cov[E(z_i | y_i)]$ using $\hat{M}_{SIR} = \sum_{g=1}^G w_g \hat{m}_g \hat{m}_g'$ whose maximum rank equals $\min\{G-1, K\}$ because $\sum_{g=1}^G w_g \hat{m}_g = 0$, where G is the number of slices and K is the number of explanatory variables. The binary dependent variable implies that we have only two slices in Step 2 of the SIR algorithm, i.e., $G=2$. So, SIR based on first-moment information $E(z_i | y_i)$ can only identify single-index, binary choice models. To identify more than one index, one needs second-moment based SIR method (Li 1991) or Sliced Average Variance Estimate (Cook and Weisberg 1991).

Remark 2: For single-index models, J is assumed to be one. But it is possible that the single index $x_i'\beta$ may capture little information relevant for y_i . If this is true, J is essentially zero and one should reconsider his selection of explanatory variables. This is similar to a linear regression context where F test suggests that all explanatory variables except the constant term are jointly insignificant. So, the permutation test is still meaningful for single-index models.

In the next section, we demonstrate the misspecification problem and model heterogeneity in single-index, binary choice models via Monte Carlo simulation. The

² Both GAUSS and STATA codes for the SIR algorithm and permutation test are available upon request.

focus is on comparing the performance of SIR and parametric MLE in estimating index coefficients under various model settings.

4. Monte Carlo Simulations

We design four Monte Carlo (MC) experiments, each with 1000 replications. The results show that SIR outperforms Logit and Probit MLE when the latent model is not $y_i^* = x_i'\beta + \varepsilon_i$ but is nonlinear in $x_i'\beta$. But when the Probit model is the true data generating process (DGP), we show that the efficiency loss of SIR compared to MLE is small given a sample of moderate size. In addition, given the specifications (2)-(3), we find that estimating the misspecified model $F(\tilde{x}_i'\beta + \alpha x_i^D)$ with the full sample generates incorrect estimate of β , regardless of whether MLE or SIR is used. We obtain consistent and efficient estimates if we perform SIR for each stratum separately.

4.1 MC Experiment I

We generate $n = 400$ observations using the following DGP. For $i = 1, 2, \dots, 400$,

(a) $x_i = [x_{1i} \ x_{2i} \ x_{3i} \ x_{4i} \ x_{5i}]'$ whose five elements are all *iid* $N(0,1)$;

(b) $\beta = [\beta_{(1)} \ \beta_{(2)} \ \beta_{(3)} \ \beta_{(4)} \ \beta_{(5)}] = [1 \ 0 \ 1 \ 0 \ 0]'$;

(c) $y_i^* = (x_i'\beta + 2)^3 + \varepsilon_i$, where $\varepsilon_i \sim iid \ N(0,1)$;

(d) $y_i = 1[y_i^* > 0]$.

In this DGP, the latent variable y_i^* is nonlinear in $x_i'\beta$, which is one of the major sources of model misspecification discussed in Section 2. The results in Table 1

indicate that SIR performs better than Probit and Logit MLE. The estimates of SIR have smaller variances and small-sample biases. Using $\hat{\beta}_{(3)}$, the third element of estimated β , as an example, its small-sample biases are 0.05, 0.05, and 0.01 for Probit, Logit, and SIR, respectively; the corresponding standard errors are 0.308, 0.312, and 0.171.³

Table 1: Probit and Logit MLE v.s. SIR in Experiment I

Methods	Estimates	$\hat{\beta}_{(1)}$	$\hat{\beta}_{(2)}$	$\hat{\beta}_{(3)}$	$\hat{\beta}_{(4)}$	$\hat{\beta}_{(5)}$
Probit MLE	mean	1.000	0.000	1.050	0.002	-0.007
	std. err	0.000	0.205	0.308	0.207	0.210
Logit MLE	mean	1.000	0.000	1.050	0.003	-0.008
	std. err	0.000	0.208	0.312	0.210	0.212
SIR	mean	1.000	-0.002	1.010	-0.001	-0.001
	std. err	0.000	0.118	0.171	0.117	0.115

4.2 MC Experiment II

We use the same DGP as in the first experiment except that we change (c) to $y_i^* = x_i' \beta + \varepsilon_i$, where $\varepsilon_i \sim iid N(0,1)$. In this setting, Probit is the true model, and therefore Probit MLE works best, as indicated by the smallest standard error of 0.118 for $\hat{\beta}_{(3)}$ in Table 2. But the efficiency loss of SIR is trivial as the corresponding standard error is 0.122.

Table 2: Probit and Logit MLE v.s. SIR in Experiment II

Methods	Estimates	$\hat{\beta}_{(1)}$	$\hat{\beta}_{(2)}$	$\hat{\beta}_{(3)}$	$\hat{\beta}_{(4)}$	$\hat{\beta}_{(5)}$
Probit MLE	mean	1.000	0.002	1.010	0.002	0.003
	std. err	0.000	0.079	0.118	0.084	0.083
Logit MLE	mean	1.000	0.002	1.010	0.002	0.003
	std. err	0.000	0.079	0.119	0.084	0.083
SIR	mean	1.000	0.002	1.010	0.002	0.003
	std. err	0.000	0.081	0.122	0.088	0.086

³ In index models, one can only identify parameters up to scale. So, we standardize $\hat{\beta}_{(1)}$ to be one and divide other estimated parameters by $\hat{\beta}_{(1)}$ and report the ratios. Hence, the standard errors of $\hat{\beta}_{(1)}$ are zeros.

4.3 MC Experiment III

We generate $n = 400$ observations using the following DGP.

(a) For $i = 1, 2, \dots, 400$, $\tilde{x}_i = [x_{1i} \ x_{2i} \ x_{3i} \ x_{4i} \ x_{5i}]'$ whose elements are all *iid* $N(0,1)$;

(b) For the subsample $i = 1, 2, \dots, 200$, $x_i^D = 1$ and $y_i^* = (\tilde{x}_i' \beta_1 + 2)^3 + \varepsilon_i$, where

$$\beta_1 = [\beta_{1(1)} \ \beta_{1(2)} \ \beta_{1(3)} \ \beta_{1(4)} \ \beta_{1(5)}]' = [1 \ 0 \ 1 \ 0 \ 0]';$$

(c) For the subsample $i = 201, 202, \dots, 400$, $x_i^D = 0$ and $y_i^* = 2 \exp(\tilde{x}_i' \beta_2) + \varepsilon_i$, where

$$\beta_2 = [\beta_{2(1)} \ \beta_{2(2)} \ \beta_{2(3)} \ \beta_{2(4)} \ \beta_{2(5)}]' = [1 \ 0 \ 0 \ 0 \ -1]';$$

(d) For $i = 1, 2, \dots, 400$, $y_i = 1[y_i^* > 0]$ and $\varepsilon_i \sim iid N(0,1)$.

In this experiment, the categorical variable x_i^D implies heterogeneity in the model itself (i.e., different models for the subsample with $x_i^D = 1$ and the subsample with $x_i^D = 0$). In Table 3, we show that the estimates are far from the true parameters if we naively combine the dummy variable and continuous variables in one index and estimate the single equation $F(\tilde{x}_i' \beta + \alpha x_i^D)$ using the full sample ($i = 1, 2, \dots, 400$). The estimate of α should be around zero, but both Probit and Logit MLE estimates for this parameter are around 3.50 and statistically significant. The SIR method does suggest $\alpha = 0$, but it fails to separately identify the vectors β_1 and β_2 .

When we split the sample according to the categorical variable and run separate regressions for each subsample, SIR generates estimates with smaller variances and small-sample biases than MLE, as we have seen in the first MC experiment. Note that the signal is much weaker for the subsample with $x_i^D = 0$ than

for the subsample with $x_i^D = 1$, due to the fact that $E[(\tilde{x}_i' \beta_1 + 2)^3] \approx 2.5 E[\exp(\tilde{x}_i' \beta_2)]$.

This explains why the estimates from the subsample with $x_i^D = 0$ have larger standard errors and small-sample biases.

Table 3: Probit and Logit MLE v.s. SIR in Experiment III

True model	True parameters	$\beta_{(1)}$	$\beta_{(2)}$	$\beta_{(3)}$	$\beta_{(4)}$	$\beta_{(5)}$	
(subsample $x_i^D = 1$)	β_1	1	0	1	0	0	
(subsample $x_i^D = 0$)	β_2	1	0	0	0	-1	
Estimates (full sample)		$\hat{\beta}_{(1)}$	$\hat{\beta}_{(2)}$	$\hat{\beta}_{(3)}$	$\hat{\beta}_{(4)}$	$\hat{\beta}_{(5)}$	$\hat{\alpha}$
Probit MLE	mean	1.000	0.004	0.606	-0.005	-0.427	3.520
	std. err	0.000	0.204	0.231	0.190	0.212	0.782
Logit MLE	mean	1.000	0.004	0.583	-0.005	-0.452	3.490
	std. err	0.000	0.212	0.239	0.196	0.224	0.848
SIR	mean	1.000	0.000	0.575	0.000	-0.441	-0.042
	std. err	0.000	0.144	0.176	0.144	0.167	0.283
Estimates (subsample $x_i^D = 1$)		$\hat{\beta}_{1(1)}$	$\hat{\beta}_{1(2)}$	$\hat{\beta}_{1(3)}$	$\hat{\beta}_{1(4)}$	$\hat{\beta}_{1(5)}$	
Probit MLE	mean	1.000	-0.008	1.130	-0.002	0.000	
	std. err	0.000	0.327	0.624	0.311	0.347	
Logit MLE	mean	1.000	-0.007	1.130	-0.002	0.000	
	std. err	0.000	0.331	0.627	0.315	0.352	
SIR	mean	1.000	0.001	1.030	0.002	-0.007	
	std. err	0.000	0.175	0.254	0.173	0.178	
Estimates (subsample $x_i^D = 0$)		$\hat{\beta}_{2(1)}$	$\hat{\beta}_{2(2)}$	$\hat{\beta}_{2(3)}$	$\hat{\beta}_{2(4)}$	$\hat{\beta}_{2(5)}$	
Probit MLE	mean	1.000	0.050	-0.035	0.038	-1.250	
	std. err	0.000	1.160	0.910	0.982	1.750	
Logit MLE	mean	1.000	0.049	-0.041	0.042	-1.260	
	std. err	0.000	1.190	1.080	1.040	1.860	
SIR	mean	1.000	-0.004	-0.013	0.000	-1.050	
	std. err	0.000	0.255	0.263	0.243	0.387	

4.4 MC Experiment IV

We use the same DGP as in the third experiment except that the errors are now drawn from a uniform distribution with mean zero and variance one, i.e., $\varepsilon_i \sim iid unif(-\sqrt{12}/2, \sqrt{12}/2)$. The non-normal errors make the Probit and Logit specifications more problematic. In Table 4, Probit and Logit MLE exhibit large standard errors (e.g., 15.90 and 3.99 for $\hat{\beta}_{2(5)}$) in the subsample with $x_i^D = 0$ (i.e., the weak signal case).

Table 4: Probit and Logit MLE v.s. SIR in Experiment IV

True model	True parameters	$\beta_{(1)}$	$\beta_{(2)}$	$\beta_{(3)}$	$\beta_{(4)}$	$\beta_{(5)}$	
(subsample $x_i^D = 1$)	β_1	1	0	1	0	0	
(subsample $x_i^D = 0$)	β_2	1	0	0	0	-1	
Estimates (full sample)		$\hat{\beta}_{(1)}$	$\hat{\beta}_{(2)}$	$\hat{\beta}_{(3)}$	$\hat{\beta}_{(4)}$	$\hat{\beta}_{(5)}$	$\hat{\alpha}$
Probit MLE	mean	1.000	-0.006	0.589	0.000	-0.458	3.350
	std. err	0.000	0.186	0.219	0.185	0.200	0.757
Logit MLE	mean	1.000	-0.006	0.565	0.000	-0.484	3.310
	std. err	0.000	0.193	0.225	0.191	0.212	0.811
SIR	mean	1.000	-0.002	0.555	-0.001	-0.468	0.050
	std. err	0.000	0.138	0.167	0.141	0.158	0.281
Estimates (subsample $x_i^D = 1$)		$\hat{\beta}_{1(1)}$	$\hat{\beta}_{1(2)}$	$\hat{\beta}_{1(3)}$	$\hat{\beta}_{1(4)}$	$\hat{\beta}_{1(5)}$	
Probit MLE	mean	1.000	-0.005	1.110	0.000	0.008	
	std. err	0.000	0.318	0.608	0.335	0.327	
Logit MLE	mean	1.000	-0.005	1.110	0.000	0.008	
	std. err	0.000	0.322	0.603	0.336	0.330	
SIR	mean	1.000	-0.007	1.030	0.002	-0.004	
	std. err	0.000	0.173	0.269	0.172	0.174	
Estimates (subsample $x_i^D = 0$)		$\hat{\beta}_{2(1)}$	$\hat{\beta}_{2(2)}$	$\hat{\beta}_{2(3)}$	$\hat{\beta}_{2(4)}$	$\hat{\beta}_{2(5)}$	
Probit MLE	mean	1.000	0.027	0.238	0.007	-1.720	
	std. err	0.000	1.900	7.610	0.900	15.90	
Logit MLE	mean	1.000	-0.017	-0.053	0.024	-1.330	
	std. err	0.000	0.809	1.830	0.627	3.990	
SIR	mean	1.000	-0.002	0.000	-0.005	-1.060	
	std. err	0.000	0.258	0.232	0.232	0.361	

This experiment shows that Probit and Logit MLE are very sensitive to incorrect error distribution assumptions when $E(y_i^* | x_i)$ is nonlinear in $x_i' \beta$, the sample size is small, and the data is noisy. SIR, however, works well under such circumstances (e.g., a small standard error of 0.361 for $\hat{\beta}_{2(5)}$) because it imposes no restrictions on the error term ε_i and the latent model $E(y_i^* | x_i)$.

Together, the MC experiments suggest that SIR can estimate coefficients of single-index, binary choice models better than parametric MLE in general settings where both the latent model and its error distribution are unknown. Given the technical difficulties of semiparametric methods discussed in Section 1, we foresee that the SIR-Nonparametric two-step method will become popular among applied

researchers. In the next section, we give an example to demonstrate this new estimation method.

5. Application to Treatment Evaluation

There is an extensive literature devoted to evaluating the impact of social programs on program participants. The assignment of individuals to these programs is often non-random as social assistance is generally targeted towards those most in need. For this reason, the difference in average outcomes of participants and non-participants is a biased estimate for the causal impact of program intervention. Various quasi-experimental methods have been proposed to reduce the selection bias due to non-random assignment and recover the true treatment effect. For a detailed overview of these methods, see Heckman *et.al.* (1998a and 1998b), Cameron and Trivedi (2005), and Imbens and Wooldridge (2008). In this application, we revisit the propensity score matching method, and we compare the estimated propensity scores and treatment effects using the SIR-Nonparametric method, Probit and Logit MLE.

To proceed, we introduce the following notations and definitions. Let $\{m_i, x_i, D_i ; i = 1, \dots, n\}$ be the vector of observations on a scalar-valued outcome variable m , a vector of observable variables x , and a binary indicator of treatment D . The primary interest of this application is to identify the population average treatment effect on the treated (ATET), defined as

$$(7) \quad ATET = E[m_{1i} - m_{0i} \mid D_i = 1].$$

Here, m_{1i} and m_{0i} denote the outcomes of an individual i when $D_i = 1$ and $D_i = 0$, respectively. The ATET can be identified under the *ignorability assumption* of Rubin (1978)

$$(8) \quad m_0 \perp D \mid x,$$

which implies that

$$(9) \quad \begin{aligned} ATET &= E_x \left\{ E \left[m_{1i} - m_{0i} \mid x_i, D_i = 1 \right] \mid D_i = 1 \right\} \\ &= E_x \left\{ E \left[m_{1i} \mid x_i, D_i = 1 \right] - E \left[m_{0i} \mid x_i, D_i = 0 \right] \mid D_i = 1 \right\}. \end{aligned}$$

The problem is that one cannot observe $E \left[m_{0i} \mid x_i, D_i = 0 \right]$ when $D_i = 1$. One may use matching methods to approximate $E \left[m_{0i} \mid x_i, D_i = 0 \right]$ based on observable x covariates. However, if the x covariates are of high dimension, the matching method becomes impractical. Rosenbaum and Rubin (1983) proposed using propensity scores, i.e., $p(x) = \Pr(D = 1 \mid X = x)$, to facilitate matching under the *conditional independence* assumption

$$(10) \quad m_0, m_1 \perp D \mid x,$$

which in turn implies

$$(11) \quad m_0, m_1 \perp D \mid p(x).$$

Given condition (11), the ATET derived in (9) can be rewritten as

$$(12) \quad \begin{aligned} ATET &= E_x \left\{ E \left[m_{1i} \mid p(x_i), D_i = 1 \right] - E \left[m_{0i} \mid p(x_i), D_i = 0 \right] \mid D_i = 1 \right\} \\ &= E_x \left\{ E \left[m_{1i} \mid p(x_i) \right] - E \left[m_{0i} \mid p(x_i) \right] \right\}. \end{aligned}$$

Matching methods pair program participants with non-participants based on the degree of similarity in the estimated propensity scores. Exact matching, nearest-neighbor matching, kernel matching, and local linear matching are some of the popular matching methods.

For simplicity, we use the nearest-neighbor matching method, which estimates ATET using

$$(13) \quad \widehat{ATE} = n_T^{-1} \sum_{i \in \{D=1\}} [m_{1i} - m_{0i^*}],$$

where n_T denotes the number of treated units being matched with control units and y_{0i^*} is the outcome of an untreated unit i^* satisfying

$$(14) \quad i^* = \left\{ j \mid \min | p(x_j) - p(x_i) | \forall j \in \{D=0\} \right\}.$$

The propensity score $p(x)$ is usually estimated using parametric single-index, binary choice models $p(x'\beta)$, such as Probit and Logit. When these models are misspecified, $\hat{\beta}_{MLE}$ is inconsistent and the fitted $\hat{p}(x_i'\hat{\beta}_{MLE})$ is an incorrect estimate of propensity score. As a result, the propensity score matching method may yield biased estimates of the ATET. To demonstrate the advantage of the SIR-Nonparametric method over the conventional parametric methods, we use the National Supported Work (NSW) data on the treatment group and one of the non-experimental control group data sets (PSID-1) constructed by Lalonde (1986) from the Panel Study of Income Dynamics.⁴

First, we divide the data into eight sub-groups based on three dummy variables --- race, marital status and high-school degree status (see Table 5 for details).⁵

Table 5: Sub-Groups Based on the Three Dummy Variables

Subgroup#	Race	Married	Nodegree	#Treated units	#PSID controls units
1	1	1	1	25	291
2	1	1	0	7	276
3	1	0	1	97	76
4	1	0	0	38	62
5	0	1	1	1	365
6	0	1	0	2	1225
7	0	0	1	8	28
8	0	0	0	7	167
Total				297	2,490

⁴ Data are from Rajeev Dehejia's website <http://www.nber.org/~rdehejia/nswdata.html>.

⁵ Race =1 if non-white, 0 if white; Married =1 if married, 0 if single; Nodegree=1 if no high school degree/diploma, 0 otherwise.

For each sub-group, we allow for a different nonparametric propensity score function

$$(15) \quad p_{is} = F_s(\tilde{x}'_{is} \beta_s) \quad \forall i \in s,$$

where $s = 1, 2, \dots, 8$ indexes the eight sub-groups and each β_s represents a column vector of index coefficients. The observed \tilde{x} comprises four continuous variables --- age, educ, RE74, and RE75. ‘Age’ is defined as age in years in 1974, ‘educ’ measures number of years of schooling in 1974, and ‘RE74’ and ‘RE75’ are real earnings in 1974 and 1975 respectively and measured in thousand of dollars. The earnings refer to the pre-intervention period as the NSW program was administered between 1975 and 1977.

We apply SIR to estimate the index coefficients β_s for each sub-group. In Table 6, we report the estimated index coefficients using SIR as well as those using Probit and Logit MLE. Cook and Yin’s permutation test following the SIR procedure indicates only one significant index for sub-groups 1, 2, 3, 4, 7, and 8 at the 5% significance level. For sub-groups 2 and 5-8, the index coefficients are not estimated precisely because of too few treated units. These sub-groups may be omitted given that they are not important sources of variation in the data. A higher level of aggregation can be applied, requiring the researcher’s discretion.

The results in panels A, B, and C indicate that the estimates of index coefficients are sensitive to the three methods. For example, the standardized index coefficient estimates for sub-group 1 are (1, -2.19, 1.12, -0.11), (1, -2.11, 4.11, -1.14), and (1, -1.92, 4.35, -0.96) when using SIR, Probit MLE, and Logit MLE, respectively. Different estimates naturally raise the question about which method to use in practice. The answer depends on the true data generating process, which is unknown. Given a misspecified propensity score function, the MLE of index coefficients is inconsistent, and the inconsistency carries through to the estimated treatment effects (Drake 1993).

Among the three methods, SIR is least demanding on model specification and its root- n consistent estimate of index coefficients has more credibility.

Table 6: Estimated Index Coefficients ($\hat{\beta}_s$) Using the Three Methods

Subgroup#	Age	Education	RE74	RE75	Jointly significant?
<i>A. Estimates Using SIR Method</i>					
1	-0.283 (0.043)	0.621 (0.172)	-0.316 (0.080)	0.032 (0.078)	Yes
2	-0.056 (0.200)	0.178 (1.190)	-0.055 (0.250)	-0.196 (0.228)	Yes
3	-0.225 (0.021)	0.239 (0.099)	-0.074 (0.042)	-0.320 (0.050)	Yes
4	0.306 (0.029)	0.225 (0.154)	-0.086 (0.037)	-0.129 (0.034)	Yes
5	-0.342 (0.369)	-0.326 (2.150)	-0.463 (0.539)	-0.012 (0.504)	No
6	-0.061 (0.779)	-0.266 (3.920)	0.047 (0.934)	-0.211 (0.938)	No
7	-0.067 (0.067)	0.330 (0.398)	-0.067 (0.104)	-0.513 (0.096)	Yes
8	0.153 (0.089)	-1.310 (0.369)	-0.192 (0.105)	-0.049 (0.101)	Yes
<i>B. Estimates Using Probit MLE</i>					
1	-0.057 (0.018)	0.120 (0.079)	-0.234 (0.054)	0.065 (0.041)	Yes
2	-0.020 (0.027)	-0.006 (0.178)	0.006 (0.025)	-0.097 (0.037)	Yes
3	-0.041 (0.015)	0.061 (0.069)	-0.044 (0.028)	-0.196 (0.046)	Yes
4	0.097 (0.062)	-0.239 (0.218)	-0.015 (0.042)	-0.382 (0.115)	Yes
5	n/a	n/a	n/a	n/a	
6	-0.060 (0.050)	-0.231 (0.260)	-0.029 (0.051)	-0.242 (0.222)	No
7	n/a	n/a	n/a	n/a	
8	-0.017 (0.033)	-0.710 (0.330)	-0.197 (0.129)	-0.032 (0.098)	Yes
<i>C. Estimates Using Logit MLE</i>					
1	-0.112 (0.035)	0.215 (0.162)	-0.487 (0.121)	0.107 (0.094)	Yes
2	-0.044 (0.056)	-0.008 (0.361)	-0.009 (0.059)	-0.196 (0.076)	Yes
3	-0.068 (0.025)	0.112 (0.121)	-0.081 (0.054)	-0.332 (0.082)	Yes
4	0.168 (0.107)	-0.420 (0.38)	-0.028 (0.071)	-0.643 (0.194)	Yes
5	n/a	n/a	n/a	n/a	
6	-0.130 (0.108)	-0.536 (0.637)	-0.067 (0.120)	-0.575 (0.525)	No
7	n/a	n/a	n/a	n/a	
8	-0.045 (0.059)	-1.362 (0.701)	-0.365 (0.244)	-0.058 (0.191)	Yes

Note: (i) The numbers in parentheses are the estimated standard errors.

(ii) For sub-groups 5 and 7, MLE fails to generate estimates for Probit and Logit models.

Next, we estimate the propensity score function using kernel regression of the treatment dummy, D_i , on the estimated inverse regression variate, $\tilde{x}'_i \hat{\beta}_s$, for $i \in s$ and $s = 1, 2, \dots, 8$. Specifically, we calculate

$$(16) \quad \hat{p}_{is} = \frac{\sum_{j=1}^{n_s} K\left(h^{-1}(\tilde{x}'_i \hat{\beta}_s - \tilde{x}'_j \hat{\beta}_s)\right) D_j}{\sum_{j=1}^{n_s} K\left(h^{-1}(\tilde{x}'_i \hat{\beta}_s - \tilde{x}'_j \hat{\beta}_s)\right)},$$

where $i, j \in s$, n_s is the sample size of sub-group s , h denotes a bandwidth, and $K(\cdot)$ is a user-specified kernel weighting function.

In Figure 1, we plot the estimated propensity score functions. These graphs confirm the two major concerns in this paper. First, parametric specifications may not be adequate for capturing the rich patterns of nonlinearity in the data. Clearly, neither Probit nor Logit specification fit the data well. Both parametric models impose a monotonic relationship between $p(\tilde{x}'_i\beta)$ and $\tilde{x}'_i\beta$.⁶ However, the nonparametric propensity score functions suggest that this is not the case for most of the sub-groups.

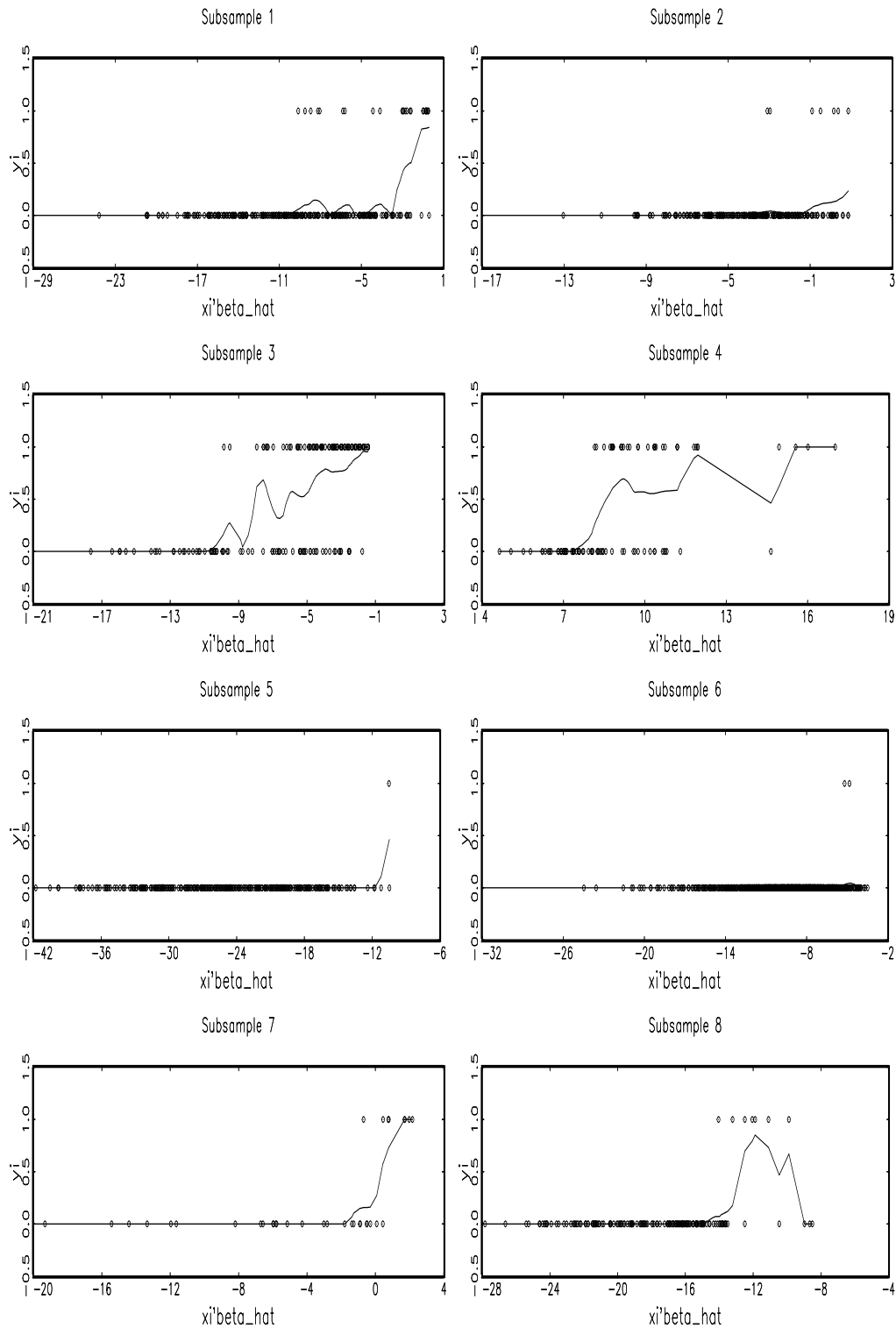
Second, substantial model heterogeneity exists as indicated by different patterns of $\hat{p}(\tilde{x}'_{i \in s}\hat{\beta}_s)$ across the eight sub-groups. None of the estimated propensity score functions of sub-groups 1-7 can be obtained by vertically or horizontally shifting the estimated propensity score function of sub-group 8 (the benchmark with the three dummy variables being zeros). Thus, the common practice of estimating a single equation with pooled data from various socio-economic groups may obscure treatment heterogeneity in the data.

Finally, we calculate the ATET for each sub-group using the estimated propensity scores. The outcome variable is RE78, the real earnings in 1978 (a year after the NSW project was completed) measured in thousand of dollars. Within each sub-group, we calculate the differences in RE78 between individuals in the treatment group and their matched counterparts in the control group. We average these differences to obtain the estimated ATET and report the results in Table 7. We focus on sub-groups 1 (non-white, married, nodegree), 3 (non-white, single, nodegree) and

⁶ Even some of semiparametric methods have the same monotonicity requirement, such as Han's maximum rank correlation estimator (1987).

4 (non-white, single, with degree) because too few matched cases in sub-groups 2 and 4-8 may introduce bias to the ATET estimates.⁷

Figure 1: Nonparametric Propensity Score Function Using the SIR Variate



⁷ There are seven matches in sub-group 2, only one match in sub-groups 5-7, and four matches in sub-group 8.

Table 7: Estimates of the ATET Based on the Three Methods

Subgroup#	<i>SIR-Nonparametric</i>		<i>Probit MLE</i>		<i>Logit MLE</i>	
	# Matches	ATET	# Matches	ATET	# Matches	ATET
1	25	-4.41 (3.60)	11	-2.76 (3.31)	11	-3.21 (3.58)
3	85	0.84 (1.79)	84	1.50 (1.65)	84	1.39 (1.54)
4	30	-1.73 (3.70)	30	-1.15 (3.85)	30	-0.62 (3.84)

Note: (i) ATET is measured in thousand of dollars;
(ii) The numbers in round brackets are bootstrapped standard errors with 1000 replications.

Clearly, there is substantial treatment heterogeneity across the three groups no matter which method is applied. All three methods suggest that only sub-group 3 benefits from the treatment while sub-groups 1 and 4 worse off after the treatment. The difference between sub-groups 1 and 3 is caused by marriage status, indicating the treatment is more effective on single individuals on average. The difference between subgroups 3 and 4 is caused by education, which implies that the NSW program may have targeted at those without high school degree.

Moreover, the three methods do not result in the same magnitude of estimated ATET. When the ATET is positive (e.g., sub-group 3), the SIR-Nonparametric method suggests a smaller treatment effect than the parametric MLE methods. When the ATET is negative (e.g., sub-groups 1 and 4), the SIR-Nonparametric method suggests a larger negative treatment effect than the parametric MLE methods. These results show that applied researcher should pay attention to model specification as well as heterogeneity when using single-index, binary-choice models.

6. Concluding Remarks

In this paper, we propose a SIR-Nonparametric method for analyzing single-index, binary-choice models in a general framework. The method does not require fully specifying a parametric model but generates root- n consistent index coefficient

estimates. In addition, we allow for model heterogeneity, which can better capture diverse economic decisions and outcomes across socio-economic groups. Thus, the proposed new method enriches the toolkit for econometric modelling and policy analysis.

There are at least two possible extensions to this modelling exercise. The first is to investigate second-moment based dimension reduction techniques, such as SIR-II (Li 1991) and Sliced Average Variance Estimate (SAVE, Cook and Weisberg 1991). These methods allow for multiple indices in binary choice models, which can potentially capture more information than first-moment based SIR used in this paper. The second possibility is to design a more efficient matching method for program evaluation. The propensity score matching based on a single-index, binary-choice model may suffer information loss and bias the estimated treatment effects. Kernel matching using estimated indices from aforementioned second-moment based dimension reduction methods may be an interesting direction worth pursuing in the future.

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