

Mis-classified, Binary, Endogenous Regressors: Identification and Inference*

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Abstract

This paper studies identification and inference for the effect of a mis-classified, binary, endogenous regressor when a discrete-valued instrumental variable is available. We begin by showing that the only existing point identification result for this model is incorrect. We go on to derive the sharp identified set under mean independence assumptions for the instrument and measurement error, and find that these fail to point identify the effect of interest. This motivates us to consider alternative and slightly stronger assumptions: we show that adding second and third moment independence assumptions suffices to identify the model. We then turn our attention to inference. We show that both our model, and related models from the literature that assume regressor exogeneity, suffer from weak identification when the effect of interest is small. To address this difficulty, we exploit the inequality restrictions that emerge from our derivation of the sharp identified set under mean independence only. These restrictions remain informative irrespective of the strength of identification. Combining these with the moment equalities that emerge from our identification result, we propose a robust inference procedure using tools from the moment inequality literature. Our method performs well in simulations, both for the exogenous and endogenous regressor case.

Keywords: Instrumental variables, Measurement error, Endogeneity, Weak identification, Moment inequalities

JEL Codes: C10, C18, C25, C26

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1 Introduction

Additively separable model

$$y = h(T^*, \mathbf{x}) + \varepsilon$$

where ε is a mean-zero error term, T^* is an endogenous binary regressor of interest and \mathbf{x} is a vector of exogenous controls. Since T^* is binary, we can re-write this as linear in T^* conditional on \mathbf{x}

$$\begin{aligned} y &= c(\mathbf{x}) + \beta(\mathbf{x})T^* + \varepsilon \\ \beta(\mathbf{x}) &= h(1, \mathbf{x}) - h(0, \mathbf{x}) \\ c(\mathbf{x}) &= h(0, \mathbf{x}) \end{aligned}$$

Goal is to use an instrumental variable z to identify $\beta(\mathbf{x})$ when we observe not T^* but a mis-measured binary surrogate T .

How are we different from Ura?

1. We maintain nondifferential measurement error assumption throughout; Ura's main purpose is to relax it.
2. We focus on an additively separable model; Ura explicitly studies at LATE setting
3. We obtain point and partial identification results; Ura present only partial identification results

Old Introduction: Many treatments of interest in applied work are binary. To take a particularly prominent example, consider treatment status in a randomized controlled trial. Even if the randomization is pristine, which yields a valid binary instrument (the offer of treatment), subjects may select into treatment based on unobservables, and given the many real-world complications that arise in the field, measurement error may be an important concern. This paper studies the use of a discrete instrumental variable to identify the causal effect of an endogenous, mis-measured, binary treatment in a model with additively separable errors. Specifically, we consider the following model

$$y = h(T^*, \mathbf{x}) + \varepsilon \tag{1}$$

where $T^* \in \{0, 1\}$ is a mis-measured, endogenous treatment, \mathbf{x} is a vector of exogenous controls, and ε is a mean-zero error. Since T^* is potentially endogenous, $\mathbb{E}[\varepsilon|T^*, \mathbf{x}]$ may

not be zero. Our goal is to non-parametrically estimate the average treatment effect (ATE) function

$$\tau(\mathbf{x}) = h(1, \mathbf{x}) - h(0, \mathbf{x}). \quad (2)$$

using a single discrete instrumental variable $z \in \{z_k\}_{k=1}^K$. We assume throughout that z is a relevant instrument for T^* , in other words

$$\mathbb{P}(T^* = 1|z_j, \mathbf{x}) \neq \mathbb{P}(T^* = 1|z_k, \mathbf{x}), \quad \forall k \neq j. \quad (3)$$

While the structural relationship involves T^* , we observe only a noisy measure T , polluted by non-differential measurement error. In particular, we assume that

$$\mathbb{P}(T = 1|T^* = 0, z, \mathbf{x}) = \alpha_0(\mathbf{x}) \quad (4)$$

$$\mathbb{P}(T = 0|T^* = 1, z, \mathbf{x}) = \alpha_1(\mathbf{x}) \quad (5)$$

where the mis-classification error rates $\alpha_0(\mathbf{x})$ and $\alpha_1(\mathbf{x})$ can depend on \mathbf{x} but not z , and additionally that, conditional on true treatment status, observed treatment status provides no additional information about the error term. In other words, we assume that

$$\mathbb{E}[\varepsilon|T^*, T, z, \mathbf{x}] = \mathbb{E}[\varepsilon|T^*, z, \mathbf{x}]. \quad (6)$$

Although a relevant case for applied work, the setting we consider here has received little attention in the literature. The only existing result for the case of an endogenous treatment appears in an important paper by [Mahajan \(2006\)](#), who is primarily concerned with the case of an exogenous treatment. As we show below, [Mahajan's](#) identification result for the endogenous treatment case is incorrect. As far as we are aware, this leaves the problem considered in this paper completely unsolved.

We begin by showing that the proof in Appendix A.2 of [Mahajan \(2006\)](#) leads to a contradiction. Throughout his paper, [Mahajan \(2006\)](#) maintains an assumption (Assumption 4) which he calls the ‘‘Dependency Condition.’’ This assumption requires that the instrumental variable be relevant, namely that it generates variation in true treatment status. When extending his result for an exogenous treatment to the more general case of an endogenous one, however, he must impose an additional condition on the model (Equation 11), which turns out to violate the Dependency Condition. Since one cannot impose the condition in Equation 11 of [Mahajan \(2006\)](#), we go on to study the prospects for identification in this model more broadly. We consider two possibilities. First, since [Mahajan's](#) identification results require only a binary instrument, we borrow an idea from [Lewbel \(2007\)](#) and explore

whether expanding the support of the instrument yields identification based on moment equations similar to those used by Mahajan (2006). While allowing the instrument to take on additional values does increase the number of available moment conditions, we show that these moments cannot point identify the treatment effect, regardless of how many (finite) values the instrument takes on.

We then consider a new source of identifying information that arises from imposing stronger assumptions on the instrumental variable. If the instrument is not merely mean independent but in fact *statistically independent* of the regression error term, as in a randomized controlled trial or a true natural experiment, additional moment conditions become available. We show that adding a conditional second moment independence assumption on the instrument identifies the *difference* of mis-classification rates $\alpha_1(\mathbf{x}) - \alpha_0(\mathbf{x})$. Because these rates must equal each other when there is no mis-classification error, our result can be used to test a necessary condition for the absence of measurement error. It can also be used to construct simple and informative partial identification bounds for the treatment effect. When one of the mis-classification rates is known, this identifies the treatment effect. More generally, however, this is not the case. We go on to show that a conditional third moment independence assumption on the instrument point identifies both $\alpha_0(\mathbf{x})$ and $\alpha_1(\mathbf{x})$ and hence the ATE function $\tau(\mathbf{x})$. Both our point identification and partial identification results require only a binary instrument, and lead to simple, closed-form method of moments estimators.

This project is still in progress. The present draft focuses on establishing identification in the simplest possible way: by directly solving a set of equations implied by conditional moment restrictions on ε . Additional results regarding efficient estimation and sharp bounds for α_0, α_1 under weaker conditions on the instrumental variable are currently in progress. For some additional discussion of these results, see our conclusion below in Section 4.

The remainder of this paper is organized as follows. In section 2 we discuss the literature in relation to the problem considered here. Section 3 introduces notation and assumptions, and presents our main results. Section 4 concludes. All proofs appear in the Appendix.

Old Literature Review: Measurement error is a pervasive feature of economic data, motivating a long tradition of measurement error modelling in econometrics. The textbook case considers a continuous regressor (treatment) subject to classical measurement error in a linear model. In this setting, the measurement error is assumed to be unrelated to the true, unobserved, value of the treatment of interest. Regardless of whether this unobserved treatment is exogenous or endogenous, a single valid instrument suffices to identify its effect. When an instrument is unavailable, Lewbel (1997) shows that higher moment assumptions

can be used to construct one, provided that the mis-measured treatment is exogenous. When it is endogenous, [Lewbel \(2012\)](#) uses a heteroskedasticity assumption to obtain identification.

Departures from the linear, classical measurement error setting pose serious identification challenges. One strand of the literature considers relaxing the assumption of linearity while maintaining that of classical measurement error. [Schennach \(2004\)](#), for example, uses repeated measures of each mis-measured treatment to obtain identification, while [Schennach \(2007\)](#) uses an instrumental variable. Both papers consider the case of exogenous treatments.¹ More recently, [Song et al. \(2015\)](#) rely on a repeated measure of the mis-measured treatment and the existence of a set of additional regressors, conditional upon which the treatment of interest is unrelated to the unobservables, to obtain identification. Another strand of the literature considers relaxing the assumption of classical measurement error, by allowing the measurement error to be related to the true value of the unobserved treatment. [Chen et al. \(2005\)](#) obtain identification in a general class of moment condition models with mis-measured data by relying on the existence of an auxiliary dataset from which they can estimate the measurement error process. In contrast, [Hu and Shennach \(2008\)](#) and [Song \(2015\)](#) rely on an instrumental variable and an additional conditional location assumption on the measurement error distribution. More recently, [Hu et al. \(2015\)](#) use a continuous instrument to identify the ratio of partial effects of two continuous regressors, one measured with error, in a linear single index model.

Many treatments of interest in economics, however, are binary, and in this case classical measurement error is impossible. Because a true 1 can only be mis-measured as a 0 and a true 0 can only be mis-measured as a 1, the measurement error must be *negatively* correlated with the true treatment status ([Aigner, 1973](#); [Bollinger, 1996](#)). For this reason, even in a textbook linear model, the instrumental variables estimator can only remove the effect of endogeneity, not that of measurement error ([Frazis and Loewenstein, 2003](#)). Measurement error in a discrete variable is usually called mis-classification.² The simplest form of mis-classification is so-called *non-differential* measurement error. In this case, conditional on true treatment status, and possibly a set of exogenous covariates, the measurement error is assumed to be unrelated to all other variables in the system.

A number of papers have studied this problem without the use of instrumental variables under the assumption that the mis-measured binary treatment is exogenous. The first to address this problem was [Aigner \(1973\)](#), who characterized the asymptotic bias of the OLS estimator in this setting, and proposed a technique for correcting it using outside information

¹For comprehensive reviews of the challenges of addressing measurement error in non-linear models, see [Chen et al. \(2011\)](#) and [Schennach \(2013\)](#).

²For general results on the partial identification of discrete probability distributions using mis-classified observations, see [Molinari \(2008\)](#).

on the mis-classification process. Another early contribution by [Bollinger \(1996\)](#) provides partial identification bounds. More recently, [Chen et al. \(2008a\)](#) use higher moment assumptions to obtain identification in a linear regression model, and [Chen et al. \(2008b\)](#) extend these results to the non-parametric setting. [van Hasselt and Bollinger \(2012\)](#) and [Bollinger and van Hasselt \(2015\)](#) provide additional partial identification results.

Continuing under the assumption of an exogenous treatment, a number of other papers in the literature have considered the identifying power of an instrumental variable, or something like one. [Black et al. \(2000\)](#) and [Kane et al. \(1999\)](#) more-or-less simultaneously pointed out that when *two* alternative measures of treatment are available, both subject to non-differential measurement error, a non-linear GMM estimator can be used to recover the treatment effect. In essence, one measure serves as an instrument for the other although the estimator is quite different from IV.³ Subsequently, [Frazis and Loewenstein \(2003\)](#) correctly note that an instrumental variable can take the place of one of the measures of treatment in a linear model with an exogenous treatment, allowing one to implement a variant of the GMM estimator proposed by [Black et al. \(2000\)](#) and [Kane et al. \(1999\)](#). However, as we will show below, the assumptions required to obtain this result are stronger than [Frazis and Loewenstein \(2003\)](#) appear to realize: the usual IV assumption that the instrument is mean independent of the regression error is insufficient for identification.

[Mahajan \(2006\)](#) extends the results of [Black et al. \(2000\)](#) and [Kane et al. \(1999\)](#) to a more general nonparametric regression setting using a binary instrument in place of one of the treatment measures. Although unaware of [Frazis and Loewenstein \(2003\)](#), [Mahajan \(2006\)](#) makes the correct assumption over the instrument and treatment to guarantee identification of the conditional mean function. When the treatment is in fact exogenous, this coincides with the treatment effect. [Hu \(2008\)](#) derives related results when the mis-classified discrete regressor may take on more than two values. [Lewbel \(2007\)](#) provides an identification result for the same model as [Mahajan \(2006\)](#) under different assumptions. In particular, the variable that plays the role of the “instrument” need not satisfy the exclusion restriction provided that it does not interact with the treatment and takes on at least three distinct values.

Much less is known about the case in which a binary, or discrete, treatment is not only mis-measured but endogenous. [Frazis and Loewenstein \(2003\)](#) briefly discuss the prospects for identification in this setting. Although they do not provide a formal proof they argue, in the context of their parametric linear model, that the treatment effect is unlikely to be

³Ignoring covariates, the observable moments in this case are the joint probability distribution of the two binary treatment measures and the conditional means of the outcome variable given the two measures. Although the system is highly non-linear, it can be manipulated to yield an explicit solution for the treatment effect provided that the true treatment is exogenous.

identified unless one is willing to impose strong and somewhat unnatural conditions.⁴ The first paper to provide a formal result for this case is [Mahajan \(2006\)](#). He extends his main result to the case of an endogenous treatment, providing an explicit proof of identification under the usual IV assumption in a model with additively separable errors. As we show below, however, [Mahajan's](#) proof is incorrect.

The results we derive here most closely relate to the setting considered in [Mahajan \(2006\)](#) in that we study non-parametric identification of the effect of a binary, endogenous treatment, using a discrete instrument. Unlike [Mahajan \(2006\)](#) we consider and indeed show the necessity of using higher-moment information to identify the causal effect of interest. Unlike [Kreider et al. \(2012\)](#), who partially identify the effects of food stamps on health outcomes of children under weak measurement error assumptions, we do not rely on auxiliary data. Unlike [Shiu \(2015\)](#), who considers a sample selection model with a discrete, mis-measured, endogenous regressor, we do not rely on a parametric assumption about the form of the first-stage. Finally unlike [Ura \(2015\)](#), who studies local average treatment effects under very general forms of mis-classification but presents only partial identification results, we point identify an average treatment effect under non-differential measurement error. Moreover, unlike the identification strategies from the existing literature described above, we do not rely upon continuity of the instrument, a large support condition, or restrictions on the relationship between the true, unmeasured treatment and its observed surrogate, subject to the condition that the measurement error process is non-differential.

2 Identification Results

2.1 Baseline Assumptions

As defined in the preceding section, our model is $y = c(\mathbf{x}) + \beta(\mathbf{x})T^* + \varepsilon$, where ε is a mean-zero error term, and the parameter of interest is $\beta(\mathbf{x})$ – the effect of an unobserved, binary, endogenous regressor T^* . Suppose we observe a valid and relevant binary instrument z . We assume that the model and instrument satisfy the following conditions:

Assumption 2.1.

- (i) $y = c(\mathbf{x}) + \beta(\mathbf{x})T^* + \varepsilon$ where $T^* \in \{0, 1\}$ and $\mathbb{E}[\varepsilon] = 0$;
- (ii) $z \in \{0, 1\}$, where $0 < \mathbb{P}(z = 1|\mathbf{x}) < 1$, and $\mathbb{P}(T^* = 1|\mathbf{x}, z = 1) \neq \mathbb{P}(T^* = 1|\mathbf{x}, z = 0)$;

⁴For example, one could consider using the results of [Hausman et al. \(1998\)](#), who study regressions with a mis-classified, discrete *outcome* variable, as a first-stage in an IV setting. In principle, this approach would fully identify the mis-classification error process. Using these results, however, requires either an explicit, nonlinear, parametric model for the first stage, or an identification at infinity argument.

(iii) $\mathbb{E}[\varepsilon|\mathbf{x}, z] = 0$.

Assumptions 2.1(ii) and (iii) are the standard instrument relevance and mean independence assumptions.⁵ If T^* were observed, Assumption 2.1 would suffice to identify $\beta(\mathbf{x})$. Unfortunately we observe not T^* but a mis-classified binary surrogate T . Define the following mis-classification probabilities:

$$\alpha_0(\mathbf{x}, z) = \mathbb{P}(T = 1|T^* = 0, \mathbf{x}, z), \quad \alpha_1(\mathbf{x}, z) = \mathbb{P}(T = 0|T^* = 1, \mathbf{x}, z). \quad (7)$$

Following the existing literature for the case of an exogenous regressor (Black et al., 2000; Frazis and Loewenstein, 2003; Kane et al., 1999; Lewbel, 2007; Mahajan, 2006), we impose the following conditions on the mis-classification process.

Assumption 2.2.

(i) $\alpha_0(\mathbf{x}, z) = \alpha_0(\mathbf{x}), \alpha_1(\mathbf{x}, z) = \alpha_1(\mathbf{x})$

(ii) $\alpha_0(\mathbf{x}) + \alpha_1(\mathbf{x}) < 1$

(iii) $\mathbb{E}[\varepsilon|\mathbf{x}, z, T^*, T] = \mathbb{E}[\varepsilon|\mathbf{x}, z, T^*]$

Assumption 2.2 (i) states that the mis-classification probabilities do not depend on z . As we maintain this assumption throughout, we drop the dependence of α_0 and α_1 on z and write $\alpha_0(\mathbf{x})$ and $\alpha_1(\mathbf{x})$. Assumption 2.2 (ii) restricts the extent of mis-classification and is equivalent to requiring that T and T^* be positively correlated. Assumption 2.2 (iii) is often referred to as “non-differential measurement error.” Intuitively, it maintains that T provides no additional information about ε , and hence y , given knowledge of (T^*, z, \mathbf{x}) .

2.2 Point Identification Results from the Literature

Existing results from the literature – see for example Frazis and Loewenstein (2003) and Mahajan (2006) – establish that $\beta(\mathbf{x})$ is point identified if Assumptions 2.1–2.2 are augmented to include the following condition:

Assumption 2.3 (Joint Exogeneity). $\mathbb{E}[\varepsilon|\mathbf{x}, z, T^*] = 0$.

Assumption 2.3 strengthens the mean independence condition from Assumption 2.1 (iii) to hold *jointly* for T^* and z . By iterated expectations, this implies that T^* is exogenous, i.e. $\mathbb{E}[\varepsilon|\mathbf{x}, T^*] = 0$. If T^* is endogenous, Assumption 2.3 clearly fails. Mahajan (2006)

⁵Point out that even though Assumption 2.1 (ii) refers to the unobserved T^* , under Assumptions 2.2 (i) and (ii) we have $(p_k^* - p_\ell^*)(1 - \alpha_0 - \alpha_1) = p_k - p_\ell$ so it suffices for an *observed* first-stage to exist.

argues, however, that the following restriction, along with our Assumptions 2.1–2.2, suffices to identify $\beta(\mathbf{x})$ when T^* may be endogenous:

Assumption 2.4 (Mahajan (2006) Equation 11). $\mathbb{E}[\varepsilon|\mathbf{x}, z, T^*, T] = \mathbb{E}[\varepsilon|\mathbf{x}, T^*]$.

Assumption 2.4 does not require $\mathbb{E}[\varepsilon|\mathbf{x}, T^*]$ to be zero, but maintains that it does not vary with z . We show in Appendix B, however, that under Assumptions 2.1–2.2, Assumption 2.4 can only hold if T^* is exogenous. If z is a valid instrument and T^* is endogenous, then Assumption 2.4 implies that there is no first-stage relationship between z and T^* . As such, identification in the case where T^* is endogenous is an open question.

2.3 Partial Identification

One approach is sharp bounds under FL/Mahajan, etc. assumptions.

2.4 Point Identification

Another approach, strengthen assumptions to get point identification.

Edit from here down

Explain what would happen if Assumption 2.2 (ii) were weakened to $\alpha_0 + \alpha_1 \neq 1$.
Second moment assumption identifies the difference of mis-classification error rates.

Assumption 2.5. $\mathbb{E}[\varepsilon^2|\mathbf{x}, z] = \mathbb{E}[\varepsilon^2|\mathbf{x}]$

Additional moment assumptions to get identification

Assumption 2.6.

$$(i) \quad \mathbb{E}[\varepsilon^2|\mathbf{x}, z, T^*, T] = \mathbb{E}[\varepsilon^2|\mathbf{x}, z, T^*]$$

$$(ii) \quad \mathbb{E}[\varepsilon^3|\mathbf{x}, z] = \mathbb{E}[\varepsilon^3|\mathbf{x}]$$

Notation

$$\theta_1(\mathbf{x}) = \beta(\mathbf{x}) [1 - \{\alpha_0(\mathbf{x}) + \alpha_1(\mathbf{x})\}]^{-1} \tag{8}$$

$$\theta_2(\mathbf{x}) = [\theta_1(\mathbf{x})]^2 [1 + \{\alpha_0(\mathbf{x}) - \alpha_1(\mathbf{x})\}] \tag{9}$$

$$\theta_3(\mathbf{x}) = [\theta_1(\mathbf{x})]^3 [(1 - \{\alpha_0(\mathbf{x}) + \alpha_1(\mathbf{x})\})^2 + 6\alpha_0(\mathbf{x}) \{1 - \alpha_1(\mathbf{x})\}] \tag{10}$$

$$\begin{aligned}
& \text{Cov}(y, z|\mathbf{x}) - \text{Cov}(T, z|\mathbf{x})\theta_1(\mathbf{x}) = 0 \\
& \text{Cov}(y^2, z|\mathbf{x}) - 2\text{Cov}(yT, z|\mathbf{x})\theta_1(\mathbf{x}) + \text{Cov}(T, z|\mathbf{x})\theta_2(\mathbf{x}) = 0 \\
& \text{Cov}(y^3, z|\mathbf{x}) - 3\text{Cov}(y^2T, z|\mathbf{x})\theta_1(\mathbf{x}) + 3\text{Cov}(yT, z|\mathbf{x})\theta_2(\mathbf{x}) - \text{Cov}(T, z|\mathbf{x})\theta_3(\mathbf{x}) = 0
\end{aligned}$$

$$\begin{aligned}
q(\mathbf{x}) &= \mathbb{P}(z = 1|\mathbf{x}) \\
\pi(\mathbf{x}) &= \text{Cov}(T, z|\mathbf{x}) \\
\eta_j(\mathbf{x}) &= \text{Cov}(y^j, z|\mathbf{x}) \\
\tau_j(\mathbf{x}) &= \text{Cov}(Ty^j, z|\mathbf{x})
\end{aligned}$$

$$\begin{aligned}
\eta_1(\mathbf{x}) &= \pi(\mathbf{x})\theta_1(\mathbf{x}) \\
\eta_2(\mathbf{x}) &= 2\tau_1(\mathbf{x})\theta_1(\mathbf{x}) - \pi(\mathbf{x})\theta_2(\mathbf{x}) \\
\eta_3(\mathbf{x}) &= 3\tau_2(\mathbf{x})\theta_1(\mathbf{x}) - 3\tau_1(\mathbf{x})\theta_2(\mathbf{x}) + \pi(\mathbf{x})\theta_3(\mathbf{x})
\end{aligned}$$

Both of the following two lemmas are known results from the literature. The first gives the relationship between the observed first stage probabilities and their unobserved counterparts,

Lemma 2.1. *Under Assumption 2.2,*

$$\begin{aligned}
[1 - \alpha_0(\mathbf{x}) - \alpha_1(\mathbf{x})] \mathbb{P}(T^* = 1|\mathbf{x}, z = k) &= \mathbb{P}(T = 1|\mathbf{x}, z = k) - \alpha_0(\mathbf{x}) \\
[1 - \alpha_0(\mathbf{x}) - \alpha_1(\mathbf{x})] \mathbb{P}(T^* = 0|\mathbf{x}, z = k) &= \mathbb{P}(T = 0|\mathbf{x}, z = k) - \alpha_1(\mathbf{x})
\end{aligned}$$

Proof. Simple calculation using law of total probability. \square

The second shows that the IV estimand does not equal β in the presence of mis-classification

Lemma 2.2. *Let $\eta_1(\mathbf{x}) = \text{Cov}(y, z|\mathbf{x})$ and $\pi(\mathbf{x}) = \text{Cov}(T, z|\mathbf{x})$. Then, under Assumptions 2.1 and 2.2, $\eta_1(\mathbf{x}) = \pi(\mathbf{x})\theta_1(\mathbf{x})$ where $\theta_1(\mathbf{x})$ is as defined in Equation 8.*

Proof. Immediate since $\text{Cov}(T, y|\mathbf{x}) = [1 - \alpha_0(\mathbf{x}) - \alpha_1(\mathbf{x})] \text{Cov}(T^*, z|\mathbf{x})$ by Lemma 2.1. \square

If we strengthen Assumption 2.1 (iii) to Assumption 2.3, then a binary instrument suffices to identify β under Assumptions ????. (See KRS, BBS, FL, and Mahajan. Also possibly

put a proof in the online-only appendix). However, without this additional condition β is unidentified regardless of the number of values that the instrument takes on, as we now show.⁶

Theorem 2.1 (Sharp Identified Set I). *Under Assumptions 2.1 and 2.2 (i)–(ii), the sharp identified set is characterized by*

$$\mathbb{E}[y|\mathbf{x}, z = k] = c(\mathbf{x}) + \beta(\mathbf{x}) \left[\frac{\mathbb{P}(T = 1|\mathbf{x}, z_k) - \alpha_0(\mathbf{x})}{1 - \alpha_0(\mathbf{x}) - \alpha_1(\mathbf{x})} \right]$$

and

$$\alpha_0(\mathbf{x}) \leq \mathbb{P}(T = 1|\mathbf{x}, z = k) \leq 1 - \alpha_1(\mathbf{x})$$

for all $k = 0, 1$.

In our discussion of the results for the sharp identified set, we can discuss what would happen if there were more than 2 values of k . Our method of proof never actually relies on there being only a binary instrument. You're not identified in any case, regardless of how many values z takes on.

Say how we get the following by plugging in the largest and smallest possible values for $\alpha_0 + \alpha_1$ and taking the difference of the expressions for $\mathbb{E}[y|z = k]$

Corollary 2.1. *Under the conditions of Theorem 2.1 the sharp identified set for $\beta(\mathbf{x})$ is the closed interval between $\Delta^y(\mathbf{x})$ and $\Delta^y(\mathbf{x})/\Delta^T(\mathbf{x})$ where $\Delta^y(\mathbf{x}) \equiv \mathbb{E}(y|\mathbf{x}, z = 1) - \mathbb{E}(y|\mathbf{x}, z = 0)$ and $\Delta^T(\mathbf{x}) \equiv \mathbb{E}(T|\mathbf{x}, z = 1) - \mathbb{E}(T|\mathbf{x}, z = 0)$.*

Talk about applied settings in which there can be one-sided mis-classification. This restricts the identified set. Following corollary collects some common cases.

Corollary 2.2. *Under the conditions of Theorem 2.1, restrictions on the misclassification probabilities shrink the sharp identified set for $\beta(\mathbf{x})$ to the closed interval between $B\Delta^y(\mathbf{x})/\Delta^T(\mathbf{x})$ and $\Delta^y(\mathbf{x})/\Delta^T(\mathbf{x})$ where*

$$(i) \alpha_0(\mathbf{x}) = 0 \text{ implies } B = \max_k \mathbb{E}(T|\mathbf{x}, z = k)$$

$$(ii) \alpha_1(\mathbf{x}) = 0 \text{ implies } B = 1 - \min_k \mathbb{E}(T|\mathbf{x}, z = k)$$

$$(iii) \alpha_0(\mathbf{x}) = \alpha_1(\mathbf{x}) \text{ implies } B = 1 - 2 \min \{ \min_k \mathbb{E}(T|\mathbf{x}, z = k), 1 - \max_k \mathbb{E}(T|\mathbf{x}, z = k) \}$$

for $k = 0, 1$, where $\Delta^T(\mathbf{x})$ and $\Delta^y(\mathbf{x})$ are as defined in Corollary 2.1.

⁶Footnote mentioning how this relates to Mahajan's mistake. He imposed an extra assumption that contradicts the existence of a first-stage. Direct the reader an appendix explaining the error.

The preceding results don't use the non-differential measurement error assumption. Further imposing non-differential measurement error – Assumption 2.2 (iii) – shrinks the identified set. We impose some additional conditions that simplify the proof. These are discussed further below.

Theorem 2.2 (Sharp Identified Set II). *Suppose that the conditional distribution of y given (\mathbf{x}, T, z) is absolutely continuous with respect to the Lebesgue measure for any values of the conditioning variables and moreover that there is no k such that $\mathbb{E}[y|\mathbf{x}, T = 0, z = k] = \mathbb{E}[y|\mathbf{x}, T = 1, z = k]$. Then, under Assumptions 2.1 and 2.2, the sharp identified set is characterized by*

$$BLAHBLAHBLAH$$

The preceding theorem assumes that y is continuously distributed, which is natural in an additively separable model and holds in our simulations and empirical examples below. If this is not the case then non-differential measurement error may impose further restrictions, although the basic idea of the argument is similar. We also imposed $\mathbb{E}[y|\mathbf{x}, T = 0, z = k] \neq \mathbb{E}[y|\mathbf{x}, T = 1, z = k]$ for any k , which holds generically. If the two means are exactly equal for some k , then the intersection of $\{(\alpha_0, \alpha_1) : \alpha_0 = p_k \text{ or } \alpha_1 = 1 - p_k\}$ with the bounds for α_0, α_1 from Theorem 2.1 must be added to the identified set.

Lemma 2.3. *Let $\eta_2(\mathbf{x}) = \text{Cov}(y^2, z|\mathbf{x})$ and $\tau_1(\mathbf{x}) = \text{Cov}(yT, z|\mathbf{x})$. Then, Under Assumptions 2.1, 2.2 and 2.5,*

$$\eta_2(\mathbf{x}) = 2\tau_1(\mathbf{x})\theta_1(\mathbf{x}) - \pi(\mathbf{x})\theta_2(\mathbf{x})$$

where $\pi(\mathbf{x})$ is as defined in Lemma 2.2 and $\theta_1(\mathbf{x})$ and $\theta_2(\mathbf{x})$ are given by Equations 8–9.

We probably want to have a corollary that establishes identification in the one-sided version of the problem. Related to this, we probably want to show that we are not in general identified from second moments even if the instrument takes on many values. This could be a real pain but on the plus side we would end up deriving the sharp identified set. One slightly confusing point is that we are now making the 2nd moment IV assumption separately from the 2nd moment non-differential measurement error assumption but we need both to get the second moment bounds for α_0 and α_1 .

Lemma 2.4. *Let $\eta_3(\mathbf{x}) = \text{Cov}(y^3, z|\mathbf{x})$ and $\tau_2(\mathbf{x}) = \text{Cov}(Ty^2, z|\mathbf{x})$. Then, under Assumptions 2.1, 2.2, 2.5 and 2.6,*

$$\eta_3(\mathbf{x}) = 3\tau_2(\mathbf{x})\theta_1(\mathbf{x}) - 3\tau_1(\mathbf{x})\theta_2(\mathbf{x}) + \pi(\mathbf{x})\theta_3(\mathbf{x})$$

where $\tau_1(\mathbf{x})$ and $\pi(\mathbf{x})$ are as defined in Lemma 2.3, and $\theta_1(\mathbf{x}), \theta_2(\mathbf{x}), \theta_3(\mathbf{x})$ are defined in Equations 8–10.

Corollary 2.3. *Suppose that $\pi(\mathbf{x}), \tau_1(\mathbf{x}), \tau_2(\mathbf{x}), \eta_1(\mathbf{x}), \eta_2(\mathbf{x})$, and $\eta_3(\mathbf{x})$ – defined in Lemmas ??? – are identified. Then, under the conditions of Lemmas ???, $\theta_1(\mathbf{x}), \theta_2(\mathbf{x})$, and $\theta_3(\mathbf{x})$ – defined in Equations 8–10 – are identified if and only if $\pi(\mathbf{x}) \neq 0$.*

Theorem 2.3 (Identification of $\beta, \alpha_0, \alpha_1$).

3 Identification-Robust Inference

4 Simulation Study

5 Coverage and Width of Confidence Intervals

α_0	α_1	β							
		0	0.25	0.5	0.75	1	1.5	2	3
0.0	0.0	90	90	90	91	90	91	90	90
	0.1	91	93	94	94	94	94	90	89
	0.2	92	93	94	94	94	94	92	90
	0.3	93	93	94	94	94	93	92	91
0.1	0.0	92	93	93	94	94	93	90	87
	0.1	93	95	96	97	97	96	92	87
	0.2	95	96	97	98	97	96	92	87
	0.3	96	98	98	98	98	95	92	88
0.2	0.0	93	93	93	93	93	93	92	89
	0.1	95	96	98	98	97	95	93	89
	0.2	97	97	98	98	97	95	92	89
	0.3	98	98	98	98	97	95	93	91
0.3	0.0	93	94	94	94	94	93	92	91
	0.1	97	97	98	98	97	95	93	89
	0.2	98	98	98	98	97	94	93	91
	0.3	99	99	99	98	98	96	95	94

Table 1: Coverage (1 - size) of 90% GMS joint test for α_0 and α_1 : $n = 1000$. Based on 10000 simulation replications.

α_0	α_1	β							
		0	0.25	0.5	0.75	1	1.5	2	3
0.0	0.0	90	90	90	91	90	91	90	90
	0.1	91	93	94	94	94	94	90	89
	0.2	92	93	94	94	94	94	92	90
	0.3	93	93	94	94	94	93	92	91
0.1	0.0	92	93	93	94	94	93	90	87
	0.1	93	95	96	97	97	96	92	87
	0.2	95	96	97	98	97	96	92	87
	0.3	96	98	98	98	98	95	92	88
0.2	0.0	93	93	93	93	93	93	92	89
	0.1	95	96	98	98	97	95	93	89
	0.2	97	97	98	98	97	95	92	89
	0.3	98	98	98	98	97	95	93	91
0.3	0.0	93	94	94	94	94	93	92	91
	0.1	97	97	98	98	97	95	93	89
	0.2	98	98	98	98	97	94	93	91
	0.3	99	99	99	98	98	96	95	94

Table 2: Coverage (1 - size) of 90% GMS joint test for α_0 and α_1 : $n = 2000$

α_0	α_1	β							
		0	0.25	0.5	0.75	1	1.5	2	3
0.0	0.0	95	95	95	96	96	96	95	95
	0.1	96	97	97	97	97	97	95	94
	0.2	96	97	98	98	97	97	96	95
	0.3	97	97	97	98	97	97	96	95
0.1	0.0	96	97	97	97	97	97	95	93
	0.1	97	98	99	99	99	98	96	92
	0.2	98	99	99	99	99	98	96	93
	0.3	99	99	99	99	99	98	96	94
0.2	0.0	97	97	97	97	97	96	96	94
	0.1	98	99	99	99	99	98	96	94
	0.2	99	99	99	99	99	98	96	94
	0.3	99	100	100	99	99	98	97	95
0.3	0.0	97	97	97	97	97	96	96	95
	0.1	99	99	99	99	99	98	97	94
	0.2	99	99	99	99	99	98	97	96
	0.3	100	100	100	99	99	98	98	97

Table 3: Coverage (1 - size) of 95% GMS joint test for α_0 and α_1 : $n = 1000$

α_0	α_1	β							
		0	0.25	0.5	0.75	1	1.5	2	3
0.0	0.0	95	95	95	96	96	96	95	95
	0.1	96	97	97	97	97	97	95	94
	0.2	96	97	98	98	97	97	96	95
	0.3	97	97	97	98	97	97	96	95
0.1	0.0	96	97	97	97	97	97	95	93
	0.1	97	98	99	99	99	98	96	92
	0.2	98	99	99	99	99	98	96	93
	0.3	99	99	99	99	99	98	96	94
0.2	0.0	97	97	97	97	97	96	96	94
	0.1	98	99	99	99	99	98	96	94
	0.2	99	99	99	99	99	98	96	94
	0.3	99	100	100	99	99	98	97	95
0.3	0.0	97	97	97	97	97	96	96	95
	0.1	99	99	99	99	99	98	97	94
	0.2	99	99	99	99	99	98	97	96
	0.3	100	100	100	99	99	98	98	97

Table 4: Coverage (1 - size) of 95% GMS joint test for α_0 and α_1 : $n = 2000$

α_0	α_1	β							
		0	0.25	0.5	0.75	1	1.5	2	3
0.0	0.0	97.7	97.7	97.6	97.7	98.0	98.0	97.4	97.9
	0.1	98.0	98.7	98.8	99.1	98.8	98.4	97.1	96.4
	0.2	98.4	98.5	98.9	98.9	98.8	98.6	98.0	97.0
	0.3	98.5	98.8	98.8	99.0	98.7	98.4	97.8	97.5
0.1	0.0	98.1	98.5	98.3	98.8	98.8	98.4	96.8	95.7
	0.1	98.6	99.1	99.5	99.6	99.6	98.8	97.7	95.2
	0.2	99.0	99.3	99.7	99.8	99.7	98.9	97.5	95.7
	0.3	99.4	99.7	99.8	99.8	99.6	99.0	98.2	96.7
0.2	0.0	98.6	98.5	98.6	98.9	98.7	98.2	97.7	97.0
	0.1	99.0	99.5	99.7	99.7	99.4	99.0	98.1	96.5
	0.2	99.5	99.7	99.8	99.7	99.4	99.0	97.8	96.8
	0.3	99.7	99.8	99.8	99.8	99.5	99.0	98.7	97.7
0.3	0.0	98.7	98.7	98.8	98.7	98.7	98.2	98.1	97.6
	0.1	99.4	99.6	99.6	99.7	99.4	98.9	98.3	96.8
	0.2	99.8	99.8	99.7	99.8	99.5	99.1	98.5	97.8
	0.3	100.0	99.9	99.9	99.8	99.6	99.5	99.1	98.8

Table 5: Coverage (1 - size) of 97.5% GMS joint test for α_0 and α_1 : $n = 1000$

α_0	α_1	β							
		0	0.25	0.5	0.75	1	1.5	2	3
0.0	0.0	97.7	97.7	97.6	97.7	98.0	98.0	97.4	97.9
	0.1	98.0	98.7	98.8	99.1	98.8	98.4	97.1	96.4
	0.2	98.4	98.5	98.9	98.9	98.8	98.6	98.0	97.0
	0.3	98.5	98.8	98.8	99.0	98.7	98.4	97.8	97.5
0.1	0.0	98.1	98.5	98.3	98.8	98.8	98.4	96.8	95.7
	0.1	98.6	99.1	99.5	99.6	99.6	98.8	97.7	95.2
	0.2	99.0	99.3	99.7	99.8	99.7	98.9	97.5	95.7
	0.3	99.4	99.7	99.8	99.8	99.6	99.0	98.2	96.7
0.2	0.0	98.6	98.5	98.6	98.9	98.7	98.2	97.7	97.0
	0.1	99.0	99.5	99.7	99.7	99.4	99.0	98.1	96.5
	0.2	99.5	99.7	99.8	99.7	99.4	99.0	97.8	96.8
	0.3	99.7	99.8	99.8	99.8	99.5	99.0	98.7	97.7
0.3	0.0	98.7	98.7	98.8	98.7	98.7	98.2	98.1	97.6
	0.1	99.4	99.6	99.6	99.7	99.4	98.9	98.3	96.8
	0.2	99.8	99.8	99.7	99.8	99.5	99.1	98.5	97.8
	0.3	100.0	99.9	99.9	99.8	99.6	99.5	99.1	98.8

Table 6: Coverage (1 - size) of 97.5% GMS joint test for α_0 and α_1 : $n = 2000$

α_0	α_1	β							
		0	0.25	0.5	0.75	1	1.5	2	3
0.0	0.0	27	33	30	14	1	0	0	0
	0.1	27	32	29	13	2	0	0	0
	0.2	26	33	32	15	4	0	0	0
	0.3	26	34	30	17	5	0	0	0
0.1	0.0	26	32	31	14	2	0	0	0
	0.1	26	36	32	16	4	0	0	0
	0.2	27	35	31	18	8	0	0	0
	0.3	25	35	32	21	11	1	0	0
0.2	0.0	26	33	30	15	3	0	0	0
	0.1	26	33	30	19	6	0	0	0
	0.2	26	35	33	22	12	1	0	0
	0.3	26	35	33	26	15	3	0	0
0.3	0.0	26	32	32	16	6	0	0	0
	0.1	24	35	33	21	11	1	0	0
	0.2	26	32	35	27	15	4	0	0
	0.3	26	35	35	28	21	7	2	0

Table 7: Percentage of simulation replications for which the standard GMM confidence interval fails to exist, either because the point estimate is NaN or the asymptotic covariance matrix is numerically singular ($n = 1000$). Based on 2000 simulation replications.

α_0	α_1	β							
		0	0.25	0.5	0.75	1	1.5	2	3
0.0	0.0	25	36	29	7	0	0	0	0
	0.1	28	36	29	7	0	0	0	0
	0.2	28	37	28	10	1	0	0	0
	0.3	27	36	28	12	2	0	0	0
0.1	0.0	27	36	27	10	0	0	0	0
	0.1	26	36	29	9	1	0	0	0
	0.2	28	38	29	13	2	0	0	0
	0.3	24	36	31	15	5	0	0	0
0.2	0.0	26	36	30	9	1	0	0	0
	0.1	25	37	29	12	2	0	0	0
	0.2	27	38	32	17	4	0	0	0
	0.3	25	39	34	20	9	1	0	0
0.3	0.0	26	37	30	10	2	0	0	0
	0.1	25	38	31	16	4	0	0	0
	0.2	27	38	34	19	9	0	0	0
	0.3	27	36	36	23	13	2	0	0

Table 8: Percentage of simulation replications for which the standard GMM confidence interval fails to exist, either because the point estimate is NaN or the asymptotic covariance matrix is numerically singular ($n = 2000$)

α_0	α_1	β							
		0	0.25	0.5	0.75	1	1.5	2	3
0.0	0.0	100	95	92	93	94	95	94	95
	0.1	100	94	91	93	94	95	96	95
	0.2	99	94	92	92	94	96	96	96
	0.3	99	94	92	92	94	96	96	95
0.1	0.0	99	95	92	92	94	95	96	96
	0.1	100	94	91	93	94	95	95	94
	0.2	100	93	91	93	94	95	95	94
	0.3	99	93	91	91	93	95	96	96
0.2	0.0	99	94	90	92	94	95	96	96
	0.1	100	93	91	92	93	95	96	94
	0.2	100	93	90	92	92	95	95	95
	0.3	100	93	90	91	93	95	95	96
0.3	0.0	100	94	91	92	95	95	96	96
	0.1	99	94	91	92	93	94	96	95
	0.2	99	93	91	92	93	94	96	96
	0.3	99	93	90	92	92	94	95	96

Table 9: Coverage of nominal 95% GMM Intervals with $n = 1000$

α_0	α_1	β							
		0	0.25	0.5	0.75	1	1.5	2	3
0.0	0.0	100	90	91	94	95	94	96	95
	0.1	100	90	91	93	95	95	95	96
	0.2	100	90	92	94	95	95	95	94
	0.3	100	90	92	93	95	95	95	94
0.1	0.0	100	90	92	92	94	95	94	96
	0.1	100	91	92	93	94	95	95	95
	0.2	100	90	92	92	95	96	95	95
	0.3	99	89	90	92	95	95	95	95
0.2	0.0	100	90	91	93	94	96	95	94
	0.1	99	91	92	93	94	96	95	96
	0.2	100	90	92	92	95	96	96	95
	0.3	99	90	91	93	95	95	96	96
0.3	0.0	100	90	91	93	94	97	95	95
	0.1	100	90	91	94	94	95	96	96
	0.2	99	90	91	92	94	96	96	96
	0.3	100	89	90	92	94	95	96	96

Table 10: Coverage of nominal 95% GMM Intervals with $n = 2000$

α_0	α_1	β							
		0	0.25	0.5	0.75	1	1.5	2	3
0.0	0.0	83.99	7.45	3.01	1.52	0.88	0.47	0.37	0.35
	0.1	85.51	7.2	3.01	1.62	1.01	0.61	0.51	0.46
	0.2	74.92	7.79	3.21	1.72	1.13	0.76	0.65	0.58
	0.3	76.66	8.02	3.19	1.78	1.29	0.91	0.79	0.7
0.1	0.0	76.59	7.46	3.2	1.59	0.99	0.61	0.51	0.46
	0.1	78.46	8.07	3.21	1.72	1.17	0.78	0.67	0.6
	0.2	77.79	7.9	3.26	1.95	1.33	0.97	0.85	0.75
	0.3	65.63	8.2	3.5	2.13	1.59	1.18	1.04	0.92
0.2	0.0	69.39	7.52	3.26	1.7	1.14	0.75	0.65	0.58
	0.1	81.48	7.79	3.27	1.95	1.34	0.97	0.84	0.75
	0.2	79.96	7.94	3.58	2.16	1.64	1.21	1.06	0.95
	0.3	85.95	8.14	3.7	2.54	1.96	1.53	1.33	1.19
0.3	0.0	87.95	7.44	3.17	1.84	1.31	0.9	0.79	0.7
	0.1	72.15	8.01	3.45	2.15	1.61	1.18	1.04	0.92
	0.2	67.84	7.6	3.75	2.63	2	1.55	1.35	1.19
	0.3	84.13	8.47	4.23	3.07	2.55	1.98	1.77	1.55

Table 11: Median Width of nominal 95% GMM Intervals with $n = 1000$

α_0	α_1	β							
		0	0.25	0.5	0.75	1	1.5	2	3
0.0	0.0	74.47	5.17	2.16	1.06	0.62	0.33	0.27	0.24
	0.1	86.02	5.07	2.25	1.13	0.7	0.43	0.36	0.33
	0.2	87.06	5.28	2.3	1.24	0.81	0.53	0.46	0.41
	0.3	83.3	5.08	2.33	1.34	0.92	0.65	0.56	0.5
0.1	0.0	71.27	5.38	2.24	1.14	0.71	0.43	0.36	0.33
	0.1	64.58	4.95	2.41	1.25	0.83	0.56	0.48	0.43
	0.2	80.03	5.31	2.39	1.38	0.98	0.69	0.6	0.53
	0.3	70.37	4.78	2.54	1.55	1.14	0.84	0.73	0.65
0.2	0.0	65.65	4.99	2.44	1.23	0.81	0.54	0.46	0.41
	0.1	71.25	5.31	2.49	1.35	0.98	0.69	0.6	0.54
	0.2	83.96	5.57	2.63	1.61	1.17	0.86	0.76	0.67
	0.3	75.88	5.83	2.88	1.85	1.44	1.09	0.95	0.85
0.3	0.0	74.62	5.23	2.41	1.32	0.92	0.65	0.56	0.5
	0.1	76.36	5.69	2.54	1.57	1.15	0.84	0.74	0.65
	0.2	91.87	5.44	2.96	1.82	1.42	1.08	0.96	0.85
	0.3	73.3	5.17	3.16	2.24	1.85	1.43	1.24	1.1

Table 12: Median Width of nominal 95% GMM Intervals with $n = 2000$

α_0	α_1	β							
		0	0.25	0.5	0.75	1	1.5	2	3
0.0	0.0	96	97	97	96	97	97	95	96
	0.1	97	99	99	99	99	100	100	99
	0.2	98	99	99	100	100	100	100	100
	0.3	97	100	100	100	100	100	100	100
0.1	0.0	97	99	99	99	100	100	100	98
	0.1	98	100	100	100	100	100	100	100
	0.2	98	100	100	100	100	100	100	100
	0.3	97	100	100	100	100	100	100	100
0.2	0.0	97	99	99	100	100	100	100	100
	0.1	98	100	100	100	100	100	100	100
	0.2	98	100	100	100	100	100	100	100
	0.3	98	100	100	100	100	100	100	100
0.3	0.0	97	99	100	100	100	100	100	100
	0.1	97	100	100	100	100	100	100	100
	0.2	98	100	100	100	100	100	100	100
	0.3	98	100	100	100	100	100	100	100

Table 13: Coverage of nominal $> 95\%$ Bonferroni Intervals with $n = 1000$

α_0	α_1	β							
		0	0.25	0.5	0.75	1	1.5	2	3
0.0	0.0	96	97	96	97	96	96	95	95
	0.1	97	98	99	100	100	100	100	99
	0.2	97	99	99	100	100	100	100	100
	0.3	97	99	100	100	100	100	100	100
0.1	0.0	97	99	99	99	100	100	100	99
	0.1	98	100	100	100	100	100	100	100
	0.2	98	100	100	100	100	100	100	100
	0.3	98	100	100	100	100	100	100	100
0.2	0.0	97	99	99	100	100	100	100	99
	0.1	98	100	100	100	100	100	100	100
	0.2	98	100	100	100	100	100	100	100
	0.3	98	100	100	100	100	100	100	100
0.3	0.0	97	100	100	100	100	100	100	100
	0.1	97	100	100	100	100	100	100	100
	0.2	97	100	100	100	100	100	100	100
	0.3	97	100	100	100	100	100	100	100

Table 14: Coverage of nominal $> 95\%$ Bonferroni Intervals with $n = 2000$

α_0	α_1	β							
		0	0.25	0.5	0.75	1	1.5	2	3
0.0	0.0	0.4	0.41	0.43	0.43	0.43	0.42	0.41	0.41
	0.1	0.45	0.47	0.54	0.59	0.63	0.7	0.75	0.86
	0.2	0.51	0.54	0.65	0.76	0.85	0.95	1.01	1.17
	0.3	0.58	0.62	0.79	0.95	1.07	1.17	1.24	1.48
0.1	0.0	0.45	0.47	0.54	0.59	0.63	0.7	0.76	0.88
	0.1	0.51	0.54	0.66	0.77	0.86	1.03	1.18	1.46
	0.2	0.58	0.63	0.8	0.98	1.12	1.38	1.55	1.88
	0.3	0.67	0.75	1	1.25	1.46	1.74	1.94	2.4
0.2	0.0	0.51	0.54	0.65	0.76	0.86	0.96	1.02	1.19
	0.1	0.58	0.63	0.81	0.99	1.14	1.42	1.64	2.08
	0.2	0.67	0.75	1.01	1.29	1.54	1.97	2.33	2.9
	0.3	0.81	0.91	1.3	1.7	2.09	2.73	3.13	3.9
0.3	0.0	0.58	0.62	0.8	0.95	1.09	1.18	1.25	1.5
	0.1	0.68	0.74	1.01	1.26	1.49	1.84	2.13	2.78
	0.2	0.81	0.91	1.3	1.7	2.11	2.8	3.4	4.48
	0.3	1.01	1.16	1.74	2.35	2.93	4.17	5.2	6.85

Table 15: Median Width of nominal $> 95\%$ Bonferroni Intervals with $n = 1000$

α_0	α_1	β							
		0	0.25	0.5	0.75	1	1.5	2	3
0.0	0.0	0.29	0.3	0.31	0.31	0.31	0.3	0.29	0.29
	0.1	0.32	0.35	0.4	0.44	0.48	0.53	0.55	0.61
	0.2	0.36	0.41	0.51	0.59	0.65	0.67	0.69	0.81
	0.3	0.41	0.48	0.64	0.76	0.81	0.8	0.85	1.01
0.1	0.0	0.32	0.35	0.4	0.44	0.48	0.53	0.56	0.62
	0.1	0.36	0.41	0.51	0.6	0.69	0.82	0.88	1.02
	0.2	0.41	0.48	0.64	0.79	0.91	1.04	1.08	1.27
	0.3	0.48	0.59	0.82	1.02	1.16	1.25	1.33	1.61
0.2	0.0	0.36	0.41	0.51	0.59	0.65	0.67	0.7	0.82
	0.1	0.41	0.48	0.65	0.79	0.92	1.09	1.21	1.52
	0.2	0.48	0.59	0.83	1.05	1.24	1.49	1.61	1.96
	0.3	0.57	0.73	1.09	1.43	1.69	1.9	2.08	2.6
0.3	0.0	0.41	0.48	0.64	0.77	0.82	0.78	0.84	1.02
	0.1	0.48	0.59	0.83	1.03	1.18	1.36	1.57	2.06
	0.2	0.57	0.73	1.1	1.43	1.71	2.11	2.45	3.18
	0.3	0.72	0.95	1.5	2.03	2.53	3.15	3.56	4.56

Table 16: Median Width of nominal $> 95\%$ Bonferroni Intervals with $n = 2000$

α_0	α_1	β							
		0	0.25	0.5	0.75	1	1.5	2	3
0.0	0.0	96	97	97	96	97	97	95	93
	0.1	97	99	99	99	99	98	96	95
	0.2	98	99	99	100	100	97	96	96
	0.3	97	100	100	100	99	96	96	96
0.1	0.0	97	99	99	99	100	98	97	95
	0.1	98	100	100	100	100	96	96	96
	0.2	98	100	100	100	99	96	96	95
	0.3	97	100	100	100	97	95	96	96
0.2	0.0	97	99	99	100	100	96	96	96
	0.1	98	100	100	100	99	96	96	96
	0.2	98	100	100	100	96	95	95	96
	0.3	98	100	100	98	95	95	95	96
0.3	0.0	97	99	100	100	100	95	96	97
	0.1	97	100	100	100	97	94	96	96
	0.2	98	100	100	98	94	94	96	96
	0.3	98	100	99	96	92	94	95	96

Table 17: Coverage of two-step CI constructed from nominal 95% GMM and nominal $> 95\%$ Bonferroni intervals: $n = 1000$

α_0	α_1	β							
		0	0.25	0.5	0.75	1	1.5	2	3
0.0	0.0	96	97	96	97	96	96	95	93
	0.1	97	98	99	100	100	98	97	96
	0.2	97	99	99	100	100	97	96	95
	0.3	97	99	100	100	99	96	96	96
0.1	0.0	97	99	99	99	100	98	96	95
	0.1	98	100	100	100	100	96	96	97
	0.2	98	100	100	100	99	96	96	97
	0.3	98	100	100	99	97	95	96	96
0.2	0.0	97	99	99	100	100	97	96	95
	0.1	98	100	100	100	98	96	96	97
	0.2	98	100	100	100	96	96	96	96
	0.3	98	100	100	97	95	95	96	96
0.3	0.0	97	100	100	100	99	98	97	96
	0.1	97	100	100	100	96	95	96	97
	0.2	97	100	100	97	94	96	96	97
	0.3	97	100	100	94	94	95	96	96

Table 18: Coverage of two-step CI constructed from nominal 95% GMM and nominal $> 95\%$ Bonferroni intervals: $n = 2000$

α_0	α_1	β							
		0	0.25	0.5	0.75	1	1.5	2	3
0.0	0.0	0.4	0.41	0.43	0.43	0.43	0.42	0.4	0.35
	0.1	0.45	0.47	0.54	0.59	0.63	0.67	0.52	0.46
	0.2	0.51	0.54	0.65	0.76	0.84	0.82	0.65	0.58
	0.3	0.58	0.62	0.79	0.95	1.05	0.96	0.79	0.7
0.1	0.0	0.45	0.47	0.54	0.59	0.63	0.67	0.51	0.46
	0.1	0.51	0.54	0.66	0.77	0.86	0.92	0.69	0.61
	0.2	0.58	0.63	0.8	0.97	1.11	1.17	0.87	0.75
	0.3	0.67	0.75	1	1.25	1.4	1.4	1.06	0.92
0.2	0.0	0.51	0.54	0.65	0.76	0.85	0.83	0.65	0.58
	0.1	0.58	0.63	0.81	0.99	1.12	1.18	0.86	0.75
	0.2	0.67	0.75	1.01	1.29	1.48	1.56	1.08	0.95
	0.3	0.81	0.91	1.3	1.67	1.95	1.77	1.35	1.2
0.3	0.0	0.58	0.62	0.8	0.95	1.07	0.95	0.8	0.7
	0.1	0.68	0.74	1.01	1.26	1.43	1.48	1.06	0.93
	0.2	0.81	0.91	1.3	1.66	1.98	1.94	1.37	1.19
	0.3	1.01	1.16	1.73	2.24	2.71	2.33	1.78	1.55

Table 19: Median width of two-step CI constructed from nominal 95% GMM and nominal > 95% Bonferroni intervals: $n = 1000$

α_0	α_1	β							
		0	0.25	0.5	0.75	1	1.5	2	3
0.0	0.0	0.29	0.3	0.31	0.31	0.31	0.3	0.29	0.25
	0.1	0.32	0.35	0.4	0.44	0.48	0.48	0.36	0.33
	0.2	0.36	0.41	0.51	0.59	0.65	0.57	0.46	0.41
	0.3	0.41	0.48	0.64	0.76	0.79	0.68	0.56	0.5
0.1	0.0	0.32	0.35	0.4	0.44	0.48	0.48	0.37	0.33
	0.1	0.36	0.41	0.51	0.6	0.68	0.65	0.48	0.43
	0.2	0.41	0.48	0.64	0.78	0.89	0.83	0.61	0.54
	0.3	0.48	0.59	0.82	1.02	1.09	0.98	0.75	0.65
0.2	0.0	0.36	0.41	0.51	0.59	0.65	0.58	0.46	0.41
	0.1	0.41	0.48	0.65	0.79	0.9	0.89	0.61	0.54
	0.2	0.48	0.59	0.83	1.05	1.2	1.22	0.77	0.67
	0.3	0.57	0.73	1.09	1.4	1.58	1.53	0.97	0.85
0.3	0.0	0.41	0.48	0.64	0.77	0.8	0.69	0.56	0.5
	0.1	0.48	0.59	0.83	1.02	1.13	1.19	0.75	0.65
	0.2	0.57	0.73	1.1	1.4	1.62	1.79	0.97	0.85
	0.3	0.72	0.95	1.49	1.93	2.36	1.58	1.25	1.1

Table 20: Median width of two-step CI constructed from nominal 95% GMM and nominal > 95% Bonferroni intervals: $n = 2000$

6 Conclusion

A Proofs

Lemma A.1 (Lemma for Appendix only with Bayes' Rule). *For mis-classification probabilities*

$$\begin{aligned} P(T^* = 1|T = 1, Z = k) &= P(T = 1|T^* = 1) \left(\frac{p_k^*}{p_k} \right) = (1 - \alpha_1) \left(\frac{p_k^*}{p_k} \right) \\ P(T^* = 1|T = 0, Z = k) &= P(T = 0|T^* = 1) \left(\frac{p_k^*}{1 - p_k} \right) = \alpha_1 \left(\frac{p_k^*}{1 - p_k} \right) \\ P(T^* = 0|T = 1, Z = k) &= P(T = 1|T^* = 0) \left(\frac{1 - p_k^*}{p_k} \right) = \alpha_0 \left(\frac{1 - p_k^*}{p_k} \right) \\ P(T^* = 0|T = 0, Z = k) &= P(T = 0|T^* = 0) \left(\frac{1 - p_k^*}{1 - p_k} \right) = (1 - \alpha_0) \left(\frac{1 - p_k^*}{1 - p_k} \right) \end{aligned}$$

Proof of Theorem 2.1. Throughout this argument we suppress dependence on \mathbf{x} for simplicity. Define $p_k = \mathbb{P}(T = 1|z = k)$ and $p_k^* = \mathbb{P}(T^* = 1|z_k)$.

We first show that so long as $\alpha_0 \leq p_k \leq 1 - \alpha_1$ then we can construct a valid joint probability distribution for (T^*, T, z) that satisfies our assumptions. First decompose the joint probability mass function as

$$p(T^*, T, z) = p(T|T^*, z)p(T^*|z)p(z).$$

By Assumption 2.2 (ii), $p(T|T^*, z) = p(T|T^*)$ and thus α_0 and α_1 fully determine $p(T|T^*, z)$. Under the proposed bounds, α_0 and α_1 are clearly valid probabilities. Since $p(z)$ is observed, it thus suffices to ensure that $p(T^*|z)$ is a valid probability mass function. By the law of total probability and Assumption 2.2 (ii),

$$p_k^* = \frac{p_k - \alpha_0}{1 - \alpha_0 - \alpha_1}.$$

and $0 \leq p_k^* \leq 1$ if and only if $\alpha_0 \leq p_k \leq 1 - \alpha_1$. Since $(p_k - p_\ell) = (p_k^* - p_\ell^*)(1 - \alpha_0 - \alpha_1)$, provided that $p_k - p_\ell \neq 0$ we have $p_k^* \neq p_\ell^*$.

We now show how to construct a valid conditional distribution for y given (T^*, T, z) that satisfies our assumptions if $\beta(p_k - \alpha_0) = (1 - \alpha_0 - \alpha_1)[\mathbb{E}(y|z_k) - c]$ for all k . Define

$$\begin{aligned} r_{tk} &\equiv \mathbb{P}(T^* = 1|T = t, z = k) & F_t(\tau) &\equiv \mathbb{P}(y \leq \tau|z = k) \\ F_{tk}(\tau) &\equiv \mathbb{P}(y \leq \tau|T = t, z = k) & F_{tk}^{t^*}(\tau) &\equiv \mathbb{P}(y \leq \tau|T^* = t^*, T = t, z = k) \\ G_k(\tau) &\equiv \mathbb{P}(\varepsilon \leq \tau|z = k) & G_{tk}^{t^*}(\tau) &\equiv \mathbb{P}(\varepsilon \leq \tau|T^* = t^*, T = t, z = k). \end{aligned}$$

Assumption 2.1 (i) implies a relationship between $G_{tk}^{t^*}$ and $F_{tk}^{t^*}$ for each t^* , namely

$$G_{tk}^0(\tau) = F_{tk}^0(\tau + c), \quad G_{tk}^1(\tau) = F_{tk}^1(\tau + c + \beta) \quad (11)$$

and thus we see that

$$\begin{aligned} G_k(\tau) &= r_{1k}p_k F_{1k}^1(\tau + c + \beta) + r_{0k}(1 - p_k)F_{0k}^1(\tau + c + \beta) \\ &\quad + (1 - r_{1k})p_k F_{1k}^0(\tau + c) + (1 - r_{0k})(1 - p_k)F_{0k}^0(\tau + c) \end{aligned} \quad (12)$$

applying the law of total probability and Bayes' rule. Moreover, again applying the law of total probability,

$$F_{tk}(\tau) = r_{tk}F_{tk}^1(\tau) + (1 - r_{tk})F_{tk}^0(\tau) \quad (13)$$

for all $t, k \in \{0, 1\}$, and by Bayes' rule,

$$r_{1k} = \frac{(1 - \alpha_1)p_k^*}{p_k}, \quad r_{0k} = \frac{\alpha_1 p_k^*}{1 - p_k}. \quad (14)$$

There are four cases, corresponding to different possibilities for the r_{tk} .

Case I: $r_{1k} = 0, r_{0k} \neq 0$ By Equation 14, this requires $\alpha_1 = 1$ which is ruled out by Assumption 2.2 (ii).

Case II: $r_{0k} = r_{1k} = 0$ By Equation 14, this requires $p_k^* = 0$ which in turn requires $p_k = \alpha_0$. Moreover, by Equation 13 we have $F_{tk}^0 = F_{tk}$, while F_{tk}^1 is undefined. Substituting into Equation 12,

$$G_k(\tau) = p_k F_{1k}(\tau + c) + (1 - p_k) F_{0k}(\tau + c) = F_k(\tau + c)$$

Now, since $F_k(\tau + c)$ is the conditional CDF of $y - c$ given that $z = k$, and G_k is the conditional CDF of ε given $z = k$, we see that Assumption 2.1 (i) is satisfied if and only if $\mathbb{E}(y|z = k) = c$. But since $p_k = \alpha_0$ in this case, $c = c + \beta(p_k - \alpha_0)/(1 - \alpha_0 - \alpha_1)$.

Case III: $r_{1k} \neq 0, r_{0k} = 0$ By Equation 14 this requires $\alpha_1 = 0$ and $p_k^* \neq 0$. By Equation 13 we have $F_{0k}^0 = F_{0k}$ and since $r_{1k} \neq 1$, we can solve to obtain

$$F_{1k}^1(\tau) = \frac{1}{r_{1k}} [F_{1k}(\tau) - (1 - r_{1k})F_{1k}^0(\tau)]$$

Substituting into Equation 12, we obtain

$$\begin{aligned} G_k(\tau) &= [(1 - p_k)F_{0k}(\tau + c) + p_k F_{1k}(\tau + c + \beta)] \\ &\quad + p_k(1 - r_{1k}) [F_{1k}^0(\tau + c) - F_{1k}^0(\tau + c + \beta)] \end{aligned}$$

Now, $F_{0k}(\tau + c)$ is the conditional CDF of $(y - c)$ given $(T = 0, z = k)$ while $F_{1k}(\tau + c + \beta)$ is the conditional CDF of $(y - c - \beta)$ given $(T = 1, z = k)$. Similarly, $F_{1k}^0(\tau + c)$ is the conditional CDF of ε given $(T^* = 0, T = 1, z = k)$ while $F_{1k}^0(\tau + c + \beta)$ is the conditional CDF of $(\varepsilon - \beta)$ given $(T^* = 0, T = 1, z = k)$. Since $G_k(\tau)$ is the conditional CDF of ε given $z = k$, we see that Assumption 2.1 (iii) is satisfied if and only if

$$\begin{aligned} 0 &= (1 - p_k)\mathbb{E}(y - c|T = 0, z = k) + p_k\mathbb{E}(y - c - \beta|T = 1, z = k) \\ &\quad + p_k(1 - r_{1k}) [\mathbb{E}(\varepsilon|T^* = 0, T = 1, z = k) - \mathbb{E}(\varepsilon - \beta|T^* = 0, T = 1, z = k)] \end{aligned}$$

Rearranging, this is equivalent to

$$\mathbb{E}(y|z = k) = c + (1 - \alpha_1)\beta \left(\frac{p_k - \alpha_0}{1 - \alpha_0 - \alpha_1} \right) = c + \beta \left(\frac{p_k - \alpha_0}{1 - \alpha_0 - \alpha_1} \right)$$

since $\alpha_1 = 0$ in this case. As explained above, $F_{0k}^0 = F_{0k}$ in the present case while F_{0k}^1 is undefined. We are free to choose any distributions for F_{1k}^0 and F_{1k}^1 that satisfy Equation 13, for example

$$F_{1k}^0 = F_{1k}^1 = F_{1k}.$$

Case IV: $r_{1k} \neq 0, r_{0k} \neq 0$ In this case, we can solve Equation 13 to obtain

$$F_{tk}^1(\tau) = \frac{1}{r_{tk}} [F_{tk}(\tau) - (1 - r_{tk})F_{tk}^0(\tau)]$$

Substituting this into Equation 12, we have

$$\begin{aligned} G_k(\tau) = & F_k(\tau + c + \beta) + p_k(1 - r_{1k}) [F_{1k}^0(\tau + c) - F_{1k}^0(\tau + c + \beta)] \\ & + (1 - p_k)(1 - r_{0k}) [F_{0k}^0(\tau + c) - F_{0k}^0(\tau + c + \beta)] \end{aligned}$$

using the fact that $F_k(\tau) = p_k F_{1k}(\tau) + (1 - p_k) F_{0k}(\tau)$. Now, $F_k(\tau + c + \beta)$ is the conditional CDF of $(y - c - \beta)$ given $z = k$, while $F_{tk}^0(\tau + c)$ is the conditional CDF of ε given $(T = t, z = k)$ and $F_{tk}^0(\tau + c + \beta)$ is the conditional CDF of $(\varepsilon - \beta)$ given $(T = t, z = k)$. Since $G_k(\tau)$ is the conditional CDF of ε given $z = k$, we see that Assumption 2.1 (iii) is satisfied if and only if

$$\begin{aligned} 0 &= \mathbb{E}[y - c - \beta | z = k] + p_k(1 - r_{1k}) [\mathbb{E}(\varepsilon | T^* = 0, T = 1, z = k) - \mathbb{E}(\varepsilon - \beta | T^* = 0, T = 1, z = k)] \\ &\quad + (1 - p_k)(1 - r_{0k}) [\mathbb{E}(\varepsilon | T^* = 0, T = 0, z = k) - \mathbb{E}(\varepsilon - \beta | T^* = 0, T = 0, z = k)] \\ 0 &= \mathbb{E}[y - c - \beta | z = k] + \beta [p_k(1 - r_{1k}) + (1 - p_k)(1 - r_{0k})] \end{aligned}$$

But since $[p_k(1 - r_{1k}) + (1 - p_k)(1 - r_{0k})] = (1 - p_k^*)$ and $p_k^* = (p_k - \alpha_0)/(1 - \alpha_0 - \alpha_1)$, this simplifies to

$$\mathbb{E}[y | z = k] = c + \beta \left(\frac{p_k - \alpha_0}{1 - \alpha_0 - \alpha_1} \right).$$

Thus, in this case we are free to choose *any* distributions for F_{tk}^0 and F_{tk}^1 that satisfy Equation 13. For example we could take $F_{tk}^0 = F_{tk}^1 = F_{tk}$. \square

Proof of Theorem 2.2. Under Assumption 2.1 (i) and Assumption 2.2 (iii), we obtain $\mathbb{E}(y | T^*, T, z) = \mathbb{E}(y | T^*, z)$. Hence, by iterated expectations

$$\begin{aligned} \mathbb{E}(y | T = 0, z = k) &= (1 - r_{0k}) \mathbb{E}(y | T^* = 0, z = k) + r_{0k} \mathbb{E}(y | T^* = 1, z = k) \\ \mathbb{E}(y | T = 1, z = k) &= (1 - r_{1k}) \mathbb{E}(y | T^* = 0, z = k) + r_{1k} \mathbb{E}(y | T^* = 1, z = k) \end{aligned}$$

where r_{tk} is defined as in the proof of Theorem 2.1. This is system of two linear equations in two unknowns: $\mathbb{E}(y | T^* = 0, z = k)$ and $\mathbb{E}(y | T^* = 1, z = k)$. After some algebra, we find that the determinant is

$$r_{1k} - r_{0k} = \left[\frac{p_k - \alpha_0}{1 - \alpha_0 - \alpha_1} \right] \left[\frac{1 - p_k - \alpha_1}{p_k(1 - p_k)} \right]$$

and thus a unique solution exists provided that $\alpha_0 \neq p_k$ and $\alpha_1 \neq 1 - p_k$. By our assumption that $\mathbb{E}[y | T = 0, z = k] \neq \mathbb{E}[y | T = 1, z = k]$, the system has no solution when the determinant condition fails. Thus, Assumption 2.2 (iii) rules out $\alpha_0 = p_k$ and $\alpha_1 = 1 - p_k$. Solving,

$$\begin{aligned} \mu_k^0 &\equiv \mathbb{E}(y | T^* = 0, z = k) = \left(\frac{1}{1 - p_k - \alpha_1} \right) [(1 - p_k) \mathbb{E}(y | T = 0, z_k) - \alpha_1 \mathbb{E}(y | z = k)] \\ \mu_k^1 &\equiv \mathbb{E}(y | T^* = 1, z = k) = \left(\frac{1}{p_k - \alpha_0} \right) [p_k \mathbb{E}(y | T = 1, z_k) - \alpha_0 \mathbb{E}(y | z = k)] \end{aligned}$$

Given (α_0, α_1) , we see that r_{tk}, μ_k^0 , and μ_k^1 are fixed. The question is whether, for a given pair

(α_0, α_1) and observed CDFs F_{tk} , we can construct valid CDFs F_{tk}^0, F_{tk}^1 such that

$$\int_{\mathbb{R}} \tau F_{tk}^0(d\tau) = \mu_k^0, \quad \int_{\mathbb{R}} \tau F_{tk}^1(d\tau) = \mu_k^1, \quad F_{tk}(\tau) = r_{tk} F_{tk}^1(\tau) + (1 - r_{tk}) F_{tk}^0(\tau)$$

where F_{tk} and F_{tk}^{t*} are as defined in the proof of Theorem 2.2. For a given pair (t, k) , there are two cases: $0 < r_{tk} < 1$ and $r_{tk} \in \{0, 1\}$.

Case I: $r_{tk} \in \{0, 1\}$ Suppose that $r_{tk} = 1$. Then, $\mu_k^1 = \mathbb{E}[y|T = t, z = k]$ so we can simply set $F_{tk}^1 = F_{tk}$. In this case F_{tk}^0 is undefined. If instead $r_{tk} = 0$, then $\mu_k^0 = \mathbb{E}[y|T = t, z = k]$ so we can simply set $F_{tk}^0 = F_{tk}$. In this case F_{tk}^1 is undefined.

Case II: $0 < r_{tk} < 1$ Define

$$m_{tk}(\xi) = \mathbb{E}[y|y \in I_{tk}(\xi), T = t, z = k] \\ I_{tk}(\xi) = [F_{tk}^{-1}(1 - \xi - r_{tk}), F_{tk}^{-1}(1 - \xi)]$$

for $t, k = 0, 1$ where $0 \leq \xi \leq 1 - r_{tk}$ and F_{tk}^{-1} is the quantile function of y given $(T = t, z = k)$. We see that m_{tk} is a decreasing function of ξ that attains its maximum at $\xi = 0$ and minimum at $\xi = 1 - r_{tk}$. Define these extrema as $\underline{m}_{tk} = m_{tk}(1 - r_{tk})$ and $\overline{m}_{tk} = m_{tk}(0)$.

Suppose first that μ_k^1 does *not* lie in the interval $[\underline{m}_{tk}, \overline{m}_{tk}]$. We show that it is impossible to construct valid CDFs F_{tk}^0 and F_{tk}^1 that satisfy $F_{tk}(\tau) = r_{tk} F_{tk}^1(\tau) + (1 - r_{tk}) F_{tk}^0(\tau)$ where F_{tk} and F_{tk}^{t*} are as defined in the proof of Theorem 2.2. Since $r_{tk} \neq 1$, we can solve the expression for F_{tk} to yield $F_{tk}^0(\tau) = [F_{tk}(\tau) - r_{tk} F_{tk}^1(\tau)] / (1 - r_{tk})$. Hence, since $r_{tk} \neq 0$, the requirement that $0 \leq F_{tk}^0(\tau) \leq 1$ implies

$$\frac{F_{tk}(\tau) - (1 - r_{tk})}{r_{tk}} \leq F_{tk}^1(\tau) \leq \frac{F_{tk}(\tau)}{r_{tk}} \quad (15)$$

Now define

$$\underline{F}_{tk}^1(\tau) = \min \{1, F_{tk}(\tau)/r_{tk}\} \\ \overline{F}_{tk}^1(\tau) = \max \{0, F_{tk}(\tau)/r_{tk} - (1 - r_{tk})/r_{tk}\}$$

Combining Equation 15 with the requirement that $0 \leq F_{tk}^1(\tau) \leq 1$, we see that

$$\overline{F}_{tk}^1(\tau) \leq F_{tk}^1(\tau) \leq \underline{F}_{tk}^1(\tau)$$

Hence \overline{F}_{tk}^1 first-order stochastically dominates F_{tk}^1 which in turn first-order stochastically dominates \underline{F}_{tk}^1 . It follows that

$$\int \tau \underline{F}_{tk}^1(d\tau) \leq \int \tau F_{tk}^1(d\tau) \leq \int \tau \overline{F}_{tk}^1(d\tau)$$

But notice that

$$\underline{m}_{tk} = \int \tau \underline{F}_{tk}^1(d\tau), \quad \mu_k^1 = \int \tau F_{tk}^1(d\tau), \quad \overline{m}_{tk} = \int \tau \overline{F}_{tk}^1(d\tau)$$

so we have $\underline{m}_{tk} \leq \mu_k^1 \leq \overline{m}_{tk}$ which contradicts $\mu_k^1 \notin [\underline{m}_{tk}, \overline{m}_{tk}]$.

Now suppose that $\mu_k^1 \in [\underline{m}_{tk}, \overline{m}_{tk}]$. Since y is assumed to follow a continuous distribution conditional on (T, z) , m_{tk} is continuous on its domain and takes on all values in $[\underline{m}_{tk}, \overline{m}_{tk}]$ by the

intermediate value theorem. Thus, there exists a ξ^* such that $m_{tk}(\xi^*) = \mu_k^1$. Now let $f_{tk}(\tau) = dF_{tk}(\tau)/d\tau$ which is non-negative by the assumption that y is continuously distributed. Define the densities

$$f_{tk}^1(\tau) = \frac{f_{tk}(\tau) \times \mathbf{1}\{\tau \in I_{tk}(\xi^*)\}}{r_{tk}}, \quad f_{tk}^0(\tau) = \frac{f_{tk}(\tau) \times \mathbf{1}\{\tau \in I_{tk}^C(\xi^*)\}}{1 - r_{tk}}.$$

Clearly $f_{tk}^1 \geq 0$ and $f_{tk}^0 \geq 0$. Integrating,

$$\begin{aligned} \int_{\mathbb{R}} f_{tk}^1(\tau) d\tau &= \frac{1}{r_{tk}} \int_{I_{tk}(\xi^*)} f_{tk}(\tau) d\tau = 1 \\ \int_{\mathbb{R}} f_{tk}^0(\tau) d\tau &= \frac{1}{1 - r_{tk}} \int_{I_{tk}^C(\xi^*)} f_{tk}(\tau) d\tau = 1 \end{aligned}$$

where I_{tk}^C is the complement of I_{tk} . And, by construction

$$r_{tk} \int_A f_{tk}^1(\tau) d\tau + (1 - r_{tk}) \int_A f_{tk}^0(\tau) d\tau = \int_A f_{tk}(\tau) d\tau$$

for any set A . Finally,

$$\int_{\mathbb{R}} \tau f_{tk}^1(\tau) d\tau = \frac{1}{r_{tk}} \int_{I_{tk}(\xi^*)} \tau f_{tk}(\tau) d\tau = m(\xi^*) = \mu_{tk}.$$

Some discussion putting all of the pieces together and explaining what the identified set looks like. In particular, what are the “edge” cases? Can’t rule out $\alpha_0 = \alpha_1 = 0$.

□

Proof of Lemma 2.3. Throughout this argument we suppress dependence on \mathbf{x} for simplicity. By Assumption 2.1 (i) and the basic properties of covariance,

$$\begin{aligned} \eta_2 &= \beta^2 \text{Cov}(T^*, z) + 2\beta [c \text{Cov}(T^*, z) + \text{Cov}(T^* \varepsilon, z)] + 2c \text{Cov}(\varepsilon, z) + \text{Cov}(\varepsilon^2, z) \\ \tau_1 &= c\pi + \text{Cov}(T\varepsilon, z) + \beta \text{Cov}(TT^*, z) \end{aligned}$$

using the fact that T^* is binary. Now, by Assumptions 2.1 (iii) and 2.5 we have $\text{Cov}(\varepsilon, z) = \text{Cov}(\varepsilon^2, z) = 0$. And, using Assumptions 2.2 (i) and (ii), one can show that $\text{Cov}(TT^*, z) = (1 - \alpha_1) \text{Cov}(T^*, z)$ and $\text{Cov}(T^*, z) = \pi / (1 - \alpha_0 - \alpha_1)$. Hence,

$$\begin{aligned} \eta_2 &= \theta_1 (\beta + 2c) \pi + 2\beta \text{Cov}(T^* \varepsilon, z) \\ 2\tau_1 \theta_1 - \pi \theta_2 &= [2\theta_1 c + 2\theta_1^2 (1 - \alpha_1) - \theta_2] \pi + 2\theta_1 \text{Cov}(T\varepsilon, z) \end{aligned}$$

but since $\theta_2 = \theta_1^2 [(1 - \alpha_1) + \alpha_0]$, we see that $[2\theta_1^2 (1 - \alpha_1) - \theta_2] = \theta_1 \beta$. Thus, it suffices to show that $\beta \text{Cov}(T^* \varepsilon, z) = \theta_1 \text{Cov}(T\varepsilon, z)$. This equality is trivially satisfied when $\beta = 0$, so suppose that $\beta \neq 0$. In this case it suffices to show that $(1 - \alpha_0 - \alpha_1) \text{Cov}(T^* \varepsilon, z) = \text{Cov}(T\varepsilon, z)$. Define $m_{tk}^* = \mathbb{E}[\varepsilon | T^* = t, z = k]$ and $p_k^* = \mathbb{P}(T^* = 1 | z = k)$. Then, by iterated expectations, Bayes’ rule, and Assumption 2.2 (iii)

$$\begin{aligned} \text{Cov}(T^* \varepsilon, z) &= q(1 - q) (p_1^* m_{11}^* - p_0^* m_{10}^*) \\ \text{Cov}(T\varepsilon, z) &= q(1 - q) \{ (1 - \alpha_1) [p_1^* m_{11}^* - p_0^* m_{10}^*] + \alpha_0 [(1 - p_1^*) m_{01}^* - (1 - p_0^*) m_{00}^*] \} \end{aligned}$$

But by Assumption 2.1 (iii), $\mathbb{E}[\varepsilon|z=k] = m_{1k}^*p_k^* + m_{0k}^*(1-p_k^*) = 0$ and thus we obtain $m_{0k}^*(1-p_k^*) = -m_{1k}^*p_k^*$. Therefore $(1-\alpha_0-\alpha_1)\text{Cov}(T^*\varepsilon, z) = \text{Cov}(T\varepsilon, z)$ as required. \square

Proof of Corollary 2.3. For ease of notation we suppress dependence on \mathbf{x} throughout this argument. Lemmas ??? yield a triangular system of linear equations in $\theta_1, \theta_2, \theta_3$. By inspection, the determinant of the system is $-\pi^3$ so a unique solution exists if and only if $\pi \neq 0$. In particular,

$$\begin{aligned}\theta_1 &= \eta_1/\pi \\ \theta_2 &= 2\tau_1\eta_1/\pi^2 - \eta_2/\pi \\ \theta_3 &= \eta_3/\pi - 3(\tau_2\eta_1 + \tau_1\eta_2)/\pi^2 + 6\tau_1^2\eta_1/\pi^3.\end{aligned}$$

\square

Proof of Lemma 2.4. Throughout this argument we suppress dependence on \mathbf{x} for simplicity. Since T^* is binary, it follows from the basic properties of covariance that,

$$\begin{aligned}\eta_3 &= \text{Cov}[(c+\varepsilon)^3, z] + 3\beta\text{Cov}[(c+\varepsilon)^2T^*, z] + 3\beta^2\text{Cov}[(c+\varepsilon)T^*, z] + \beta^3\text{Cov}(T^*, z) \\ \tau_2 &= \text{Cov}[(c+\varepsilon)^2T, z] + 2\beta\text{Cov}[(c+\varepsilon)TT^*, z] + \beta^2\text{Cov}(TT^*, z)\end{aligned}$$

By Assumptions 2.1 (iii), 2.5, and 2.6 (ii), $\text{Cov}[(c+\varepsilon)^3, z] = 0$. Expanding,

$$\begin{aligned}\eta_3 &= 3\beta\text{Cov}(T^*\varepsilon^2, z) + (3\beta^2 + 6c\beta)\text{Cov}(T^*\varepsilon, z) + (\beta^3 + 3c\beta^2 + 3c^2\beta)\text{Cov}(T^*, z) \\ \tau_2 &= c^2\text{Cov}(T, z) + \beta(\beta + 2c)\text{Cov}(TT^*, z) + \text{Cov}(T\varepsilon^2, z) + 2c\text{Cov}(T\varepsilon, z) + 2\beta\text{Cov}(TT^*\varepsilon, z)\end{aligned}$$

Now, define $s_{tk}^* = \mathbb{E}[\varepsilon^2|T^* = t, z = k]$ and $p_k^* = \mathbb{P}(T^* = 1|z = k)$. By iterated expectations, Bayes' rule, and Assumption 2.6 (i),

$$\begin{aligned}\text{Cov}(T^*\varepsilon^2, z) &= q(1-q)(p_1^*s_{11}^* - p_0^*s_{10}^*) \\ \text{Cov}(T\varepsilon^2, z) &= q(1-q)\{(1-\alpha_1)[p_1^*s_{11}^* - p_0^*s_{10}^*] + \alpha_0[(1-p_1^*)s_{01}^* - (1-p_0^*)s_{00}^*]\}\end{aligned}$$

By Assumption 2.5, $\mathbb{E}[\varepsilon^2|z=1] = \mathbb{E}[\varepsilon^2|z=0]$ and thus, by iterated expectations we have $p_1^*s_{11}^* - p_0^*s_{10}^* = -[(1-p_1^*)s_{01}^* - (1-p_0^*)s_{00}^*]$ which implies

$$\text{Cov}(T\varepsilon^2, z) = (1-\alpha_0-\alpha_1)\text{Cov}(T^*\varepsilon^2, z). \quad (16)$$

Similarly by iterated expectations and Assumptions 2.2 (i)–(ii)

$$\text{Cov}(TT^*\varepsilon, z) = q(1-q)(1-\alpha_1)(p_1^*m_{1k}^* - p_0^*m_{10}^*) = (1-\alpha_1)\text{Cov}(T^*\varepsilon, z) \quad (17)$$

where m_{tk}^* is defined as in the proof of Lemma 2.3. As shown in the proof of Lemma 2.3,

$$\begin{aligned}\text{Cov}(TT^*, z) &= (1-\alpha_1)\text{Cov}(T^*, z) \\ \text{Cov}(T^*, z) &= \pi/(1-\alpha_0-\alpha_1) \\ \text{Cov}(T^*\varepsilon, z) &= \text{Cov}(T\varepsilon, z)/(1-\alpha_0-\alpha_1)\end{aligned}$$

and combining these equalities with Equations 16 and 17, it follows that

$$\begin{aligned}\tau_2 &= 2[(1 - \alpha_1)(c + \beta) - c\alpha_0] \text{Cov}(T^*\varepsilon, z) + [(1 - \alpha_1)(c + \beta)^2 - c^2\alpha_0] \text{Cov}(T^*, z) \\ &\quad + (1 - \alpha_0 - \alpha_1) \text{Cov}(T^*\varepsilon^2, z) \\ \tau_1 &= (1 - \alpha_0 - \alpha_1) \text{Cov}(T^*\varepsilon, z) + [(1 - \alpha_1)(c + \beta) - c\alpha_0] \text{Cov}(T^*, z)\end{aligned}$$

using $\tau_1 = c\pi + \text{Cov}(T\varepsilon, z) + \beta \text{Cov}(TT^*, z)$ as shown in the proof of Lemma 2.3. Thus,

$$3\tau_2\theta_1 - 3\tau_1\theta_2 + \pi\theta_3 = K_1 \text{Cov}(T^*\varepsilon^2, z) + K_2 \text{Cov}(T^*\varepsilon, z) + K_3 \text{Cov}(T^*, z)$$

where

$$\begin{aligned}K_1 &\equiv 3\theta_1(1 - \alpha_0 - \alpha_1) \\ K_2 &\equiv 6\theta_1[(1 - \alpha_1)(c + \beta) - c\alpha_0] - 3\theta_2(1 - \alpha_0 - \alpha_1) \\ K_3 &\equiv 3\theta_1[(1 - \alpha_1)(c + \beta)^2 - c^2\alpha_0] - 3\theta_2[(1 - \alpha_1)(c + \beta) - c\alpha_0] + \theta_3(1 - \alpha_0 - \alpha_1)\end{aligned}$$

Clearly $K_1 = 3\beta$. Substituting the definitions of θ_1, θ_2 , and θ_3 from Equations 8–10, tedious but straightforward algebra likewise shows that $K_2 = 3\beta^2 + 6c\beta$ and $K_3 = \beta^3 + 3c\beta^2 + 3c^2\beta$. Therefore the coefficients of η_3 equal those of $3\tau_2 - 3\tau_1\theta_2 + \pi\theta_3$ and the result follows. \square

Proof of Theorem 2.3. For ease of notation we suppress dependence on \mathbf{x} throughout this argument. So long as $\beta \neq 0$, we can rearrange Equations 9 and 10 to obtain

$$A = \theta_2/\theta_1^2 = 1 + (\alpha_0 - \alpha_1) \quad (18)$$

$$B = \theta_3/\theta_1^3 = (1 - \alpha_0 - \alpha_1)^2 + 6\alpha_0(1 - \alpha_1) \quad (19)$$

Equation 18 gives $(1 - \alpha_1) = A - \alpha_0$. Hence $(1 - \alpha_0 - \alpha_1) = A - 2\alpha_0$ and $\alpha_0(1 - \alpha_1) = \alpha_0(A - \alpha_0)$. Substituting into Equation 19 and simplifying, $(A^2 - B) + 2A\alpha_0 - 2\alpha_0^2 = 0$. Substituting for α_0 analogously yields a quadratic in $(1 - \alpha_1)$ with *identical* coefficients. It follows that one root of $(A^2 - B) + 2Ar - 2r^2 = 0$ is α_0 and the other is $1 - \alpha_1$. Solving,

$$r = \frac{A}{2} \pm \sqrt{3A^2 - 2B} = \frac{1}{\theta_1^2} \left(\frac{\theta_2}{2} \pm \sqrt{3\theta_2^2 - 2\theta_1\theta_3} \right). \quad (20)$$

By Equations 9 and 10,

$$\begin{aligned}3\theta_2^2 - 2\theta_1\theta_3 &= 3[\theta_1^2(1 + \alpha_0 - \alpha_1)]^2 - 2\theta_1\{\theta_1^3[(1 - \alpha_0 - \alpha_1)^2 + 6\alpha_0(1 - \alpha_1)]\} \\ &= \theta_1^4\{3(1 + \alpha_0 - \alpha_1)^2 - 2[(1 - \alpha_0 - \alpha_1)^2 + 6\alpha_0(1 - \alpha_1)]\}.\end{aligned}$$

Expanding the first term we find that

$$\begin{aligned}3(1 + \alpha_0 - \alpha_1)^2 &= 3[1 + 2(\alpha_0 - \alpha_1) + (\alpha_0 - \alpha_1)^2] \\ &= 3 + 6\alpha_0 - 6\alpha_1 + 3\alpha_0^2 + 3\alpha_1^2 - 6\alpha_0\alpha_1\end{aligned}$$

and expanding the second

$$\begin{aligned}2[(1 - \alpha_0 - \alpha_1)^2 + 6\alpha_0(1 - \alpha_1)] &= 2[1 - 2(\alpha_0 + \alpha_1) + (\alpha_0 + \alpha_1)^2 + 6\alpha_0 - 6\alpha_0\alpha_1] \\ &= 2 + 8\alpha_0 - 4\alpha_1 + 2\alpha_0^2 + 2\alpha_1^2 - 8\alpha_0\alpha_1.\end{aligned}$$

Therefore

$$\begin{aligned} 3\theta_2^2 - 2\theta_1\theta_3 &= \theta_1^4 \{1 - 2\alpha_0 - 2\alpha_1 + \alpha_0^2 - \alpha_1^2 + 2\alpha_0\alpha_1\} \\ &= \theta_1^4 [(1 - \alpha_0 - \alpha_1)^2] \end{aligned}$$

which is strictly greater than zero since $\theta_1 \neq 0$ and $\alpha_0 + \alpha_1 \neq 0$. It follows that both roots of the quadratic are real. Moreover, $3\theta_2^2/\theta_1^4 - 2\theta_3/\theta_1^3$ identifies $(1 - \alpha_0 - \alpha_1)^2$. Substituting into Equation 8, it follows that β is identified up to sign. If $\alpha_0 + \alpha_1 < 1$ then $\text{sign}(\beta) = \text{sign}(\theta_1)$ so that both the sign and magnitude of β are identified. If $\alpha_0 + \alpha_1 > 1$ then $1 - \alpha_1 > \alpha_0$ so $(1 - \alpha_1)$ is the larger root of $(A^2 - B) + 2Ar - 2r^2 = 0$ and α_0 is the smaller root. \square

B Mahajan's Approach

Here we show that Mahajan's proof of identification for an endogenous treatment is incorrect. The problem is subtle so we give his argument in full detail. We continue to suppress dependence on the exogenous covariates \mathbf{x} .

The first step of Mahajan's argument is to show that if one could recover the conditional mean function of y given T^* , then a valid and relevant binary instrument would suffice to identify the treatment effect.

Assumption B.1 (Mahajan A2). *Suppose that $y = c + \beta T^* + \varepsilon$ where*

- (i) $\mathbb{E}[\varepsilon|z] = 0$
- (ii) $\mathbb{P}(T^* = 1|z_k) \neq \mathbb{P}(T^* = 1|z_\ell)$ for all $k \neq \ell$
- (iii) $\mathbb{P}(T = 1|T^* = 0, z) = \alpha_0$, $\mathbb{P}(T = 0|T^* = 1, z) = \alpha_1$
- (iv) $\alpha_0 + \alpha_1 \neq 1$
- (v) $\beta \neq 0$

Lemma B.1 (Mahajan A2). *Under Assumption ???, knowledge of the mis-classification error rates α_0, α_1 suffices to identify β .*

In his Theorem 1, Mahajan (2006) proves that α_0, α_1 can in fact be identified under the following assumptions.⁷

Assumption B.2 (Mahajan A1). *Define $\nu = y - \mathbb{E}[y|T^*]$ so that by construction we have $\mathbb{E}[\nu|T^*] = 0$. Assume that*

- (i) $\mathbb{E}[\nu|T^*, T, z] = 0$.⁸
- (ii) $\mathbb{P}(T^* = 1|z_k) \neq \mathbb{P}(T^* = 1|z_\ell)$ for all $k \neq \ell$
- (iii) $\mathbb{P}(T = 1|T^* = 0, z) = \alpha_0$, $\mathbb{P}(T = 0|T^* = 1, z) = \alpha_1$
- (iv) $\alpha_0 + \alpha_1 < 1$

⁷Technically, one additional assumption is required, namely that the conditional mean of y given T^* and any covariates would be identified if T^* were observed.

⁸This is Mahajan's Equation (I).

$$(v) \mathbb{E}[y|T^* = 0] \neq \mathbb{E}[y|T^* = 1]$$

Lemma B.2 (Mahajan Theorem 1). *Under Assumptions ???, the error rates α_0, α_1 are identified as is the conditional mean function $\mathbb{E}[y|T^*]$.*

Notice that the identification of the error rates in Lemma ??? does not depend on the interpretation of the conditional mean function $\mathbb{E}[y|T^*]$. If T^* is an exogenous treatment, the conditional mean coincides with the treatment effect; if it is endogenous, this is not the case. Either way, the meaning of α_0, α_1 is unchanged: these parameters simply characterize the mis-classification process. Based on this observation, Mahajan (2006) claims that he can rely on Lemma ??? to identify α_0, α_1 and thus the causal effect β when the treatment is endogenous via Lemma ???. To do this, he must build a bridge between Assumption ??? and Assumption ??? that allows T^* to be endogenous. Mahajan (2006) does this by imposing one additional assumption: Equation 11 in his paper.

Assumption B.3 (Mahajan Equation 11). *Let $y = c + \beta T^* + \varepsilon$ where $\mathbb{E}[\varepsilon|T^*]$ may not be zero and suppose that*

$$\mathbb{E}[\varepsilon|T^*, T, z] = \mathbb{E}[\varepsilon|T^*].$$

Lemma B.3. *Suppose that $y = c + \beta T^* + \varepsilon$ where $E[\varepsilon|z] = 0$ and define the unobserved projection error $\nu = y - \mathbb{E}[y|T^*]$. Then Assumption ??? implies that $E[\nu|T^*, T, z] = 0$, which is Assumption ???.*

To summarize, Mahajan's claim is equivalent to the proposition that under Assumptions ??? β is identified even if T^* is endogenous. although Lemmas ??? are all correct, Mahajan's claim is not.⁹ While Assumption ??? does guarantee that Assumption ??? holds, when combined with Assumption ??? it also implies that ??? fails if T^* is endogenous. The failure of Assumption ??? in turn leads to a division by zero in the solution to the linear system following Mahajan's displayed Equation 26: the system no longer has a unique solution so identification fails.¹⁰

Proposition B.1 (Lack of a First Stage). *Suppose that Assumptions ??? hold and $\mathbb{E}[\varepsilon|T^*] \neq 0$. Then $\mathbb{P}(T^* = 1|z_1) = \mathbb{P}(T^* = 1|z_2)$, violating Assumption ???.*

To understand the economic intuition behind Proposition ???, consider a simple example in which we randomize the offer of a job training program to a sample of workers to study the impact on future earnings. In this context z indicates whether a particular individual is *offered* job training by the experimenter while T^* indicates whether she actually *obtains* job training from any source, inside or outside of the experiment. We observe not T^* but a self-report T that is measured with error. In this example u contains all of the unobservable factors that determine an individual's wage.

Assumption ??? allows for endogenous treatment receipt: $\mathbb{E}[u|T^* = 1]$ may be different from $\mathbb{E}[u|T^* = 0]$. We might expect, for example, that individuals who obtain job training are more

⁹Our Lemma ??? does not in fact appear in Mahajan (2006), but it is an implicit step in his proof in Appendix A2.

¹⁰Notice that the root of the problem is the attempt to use *one* instrument to solve both the measurement error and endogeneity problems. In a setting where one had a second mis-measured surrogate for T^* *in addition* to an instrument that is conditionally mean independent of ε one could use the second surrogate as an instrument for the first to estimate α_0 and α_1 via Lemma ??? and then use the additional instrumental variable to estimate $\beta/(1 - \alpha_0 - \alpha_1)$ via the familiar Wald IV estimator. This is effectively the approach used by Battistin et al. (2014) to evaluate the returns to schooling in a setting with multiple misreported measures of educational qualifications.

motivated than those who do not, and hence earn higher wages on average. However, Assumption ??? imposes that $\mathbb{E}[u|T^* = t, z_1] = \mathbb{E}[u|T^* = t, z_2]$ for $t = 0, 1$. This has two implications. First, it means that, among those who do not obtain job training, the average value of u is the same for those who were offered training and those who were not. Second, it means that, among those who *did* obtain job training, the average value of u is the same for those who were offered training and those who were not. In other words, Assumption ??? requires that there is *no selection on unobservables*. This is exactly the opposite of what we would expect in the job training setting. For example, individuals who are offered job training but refuse it, are likely to be very different from those who are not offered training and fail to obtain it from an outside source. And herein lies the problem: Assumption ??? simultaneously allows endogeneity and rules out selection. Given that the offer of job training is randomly assigned, and hence a valid instrument, the only way to avoid a contradiction is if there is no first stage: the fraction of individuals who take up job training cannot depend on the offer of training.

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