

# Testing Monotonicity in a Finite Population

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ABSTRACT. We consider the extent to which we can learn from a completely randomized experiment whether everyone has treatment effects that are weakly of the same sign, a condition we call *monotonicity*. From a classical sampling perspective, it is well-known that monotonicity is untestable. By contrast, we show from the design-based perspective—in which the units in the population are fixed and only treatment assignment is stochastic—that the distribution of treatment effects in the finite population (and hence whether monotonicity holds) is formally *identified*. We argue, however, that the usual definition of identification is unnatural in the design-based setting because it imagines knowing the distribution of outcomes over different treatment assignments for the same units. We thus evaluate the informativeness of the data by the extent to which it enables frequentist testing and Bayesian updating. We show that frequentist tests can have nontrivial power against some alternatives, but power is generically limited. Likewise, we show that there exist (non-degenerate) Bayesian priors that never update about whether monotonicity holds. We conclude that, despite the formal identification result, the ability to learn about monotonicity from data in practice is severely limited.

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## 1. Introduction

Let  $D$  be a randomly assigned binary treatment and  $Y$  a binary outcome. Researchers are often interested in evaluating the *monotonicity* assumption that everyone has a treatment effect weakly of the same sign.<sup>1</sup> For example, if  $D$  is a medical intervention, we may be interested in whether some patients benefit from the treatment while others are harmed, which would indicate that outcomes could potentially be improved by better targeting. Likewise, if  $D$  is an instrumental variable and  $Y$  a treatment with imperfect compliance (more frequently denoted  $Z$  and  $D$ , respectively), then the monotonicity assumption is needed for two-stage least squares to have a local-average-treatment-effect interpretation (Angrist and Imbens, 1994).

There are two distinct approaches to statistical uncertainty in causal inference settings that lead to different formal definitions of monotonicity. The classical perspective views the  $n$  observed units as sampled from an infinite superpopulation. Monotonicity then imposes that there are no individuals in the superpopulation with opposite-signed treatment effects. Formally, we assume that the potential outcomes are sampled from a distribution  $g_p^*$ ,  $(y_i(0), y_i(1)) \sim g_p^*$ , where  $p = (p_{at}, p_{nt}, p_d, p_c)$  denotes the superpopulation shares of each “type”, where each type corresponds to one of four possible values for  $(y(1), y(0))$ . Borrowing from the instrumental-variables literature, we use *at* to denote an “always-taker” with  $y(0) = y(1) = 1$ , and likewise use *nt* for never-takers ( $y(0) = y(1) = 0$ ), *d* for defiers ( $y(1) = 0, y(0) = 1$ ), and *c* for compliers ( $y(1) = 1, y(0) = 0$ ). The classical definition of monotonicity is then that  $\min\{p_c, p_d\} = 0$ .

By contrast, the *design-based* perspective views the  $n$  units and their potential outcomes as fixed or conditioned upon, with statistical uncertainty arising only from the stochastic assignment of treatment. The data-generating process  $(Y_T, Y_U) \sim f_\theta$  is then parameterized by  $\theta = (\theta_{at}, \theta_{nt}, \theta_d, \theta_c)$ , where  $\theta_t$  is the *count* of how many of the  $n$  units are of type  $t$ . The design-based monotonicity assumption is then that  $\min\{\theta_c, \theta_d\} = 0$ . In sum, the classical monotonicity assumption asks whether there are any units with opposite-signed treatment effects in the superpopulation from which the sample is drawn, while the design-based version asks whether there are any opposite-signed treatment effects *among the  $n$  units at hand*.

It is well-known that data are not informative about whether monotonicity holds in the superpopulation. Suppose that we have a completely randomized experiment in which  $n_1$  of the  $n$  units are randomly assigned to treatment. The researcher then

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<sup>1</sup>Also known as monotone treatment response (Manski, 1997).

observes  $(Y_T, Y_U) = (\sum_i D_i Y_i, \sum_i (1 - D_i) Y_i)$ , summarizing how many units in each treatment group have  $Y_i = 1$ . From the superpopulation perspective, we have that  $(Y_T, Y_U) \sim g_p$  (where  $g_p$  is the push-forward of  $g_p^*$  under random assignment with probability  $n_1/n$ ). However, it is straightforward to show that  $p$  is not point-identified (see, e.g., [Heckman, Smith and Clements, 1997](#)). In particular, for any  $p_1$  that violates monotonicity, there exists a  $p_0$  satisfying monotonicity such that  $g_{p_1} = g_{p_0}$ . Hence, from the superpopulation perspective, the data provide no information as to whether monotonicity holds.<sup>2</sup>

By contrast, we show that from the design-based perspective, the type counts  $\theta$  are in fact identified according to the usual technical definition of identification: the mapping from the parameter to the distribution of the observed data,  $\theta \mapsto f_\theta$ , is one-to-one. At first blush, the typical definition of identification appears to suggest that the data *are* informative about whether the design-based version of monotonicity holds.

We argue, however, that the usual notion of identification is somewhat unnatural in the design-based setting: identification asks what we could learn if we saw repeated realizations of the outcomes under different treatment assignments for the *same* units. In practice, however, we only observe one realized treatment assignment for each of these units. It is therefore not clear whether identification in the usual sense implies that we can meaningfully *learn* about whether monotonicity holds from the data we actually observe. To evaluate the extent to which one can feasibly learn about monotonicity given a single realization of the data in the design-based setting, we ask two questions: First, to what extent can one construct frequentist tests of the null of monotonicity? Second, to what extent do Bayesians update about the probability that monotonicity holds?

From the frequentist perspective, we show that there exist tests of the design-based monotonicity assumption with non-trivial power against some alternatives, but we generally expect the power of these tests to be poor. In particular, we show that any test of monotonicity must have trivial power against some alternative. Moreover, we show that any test that has power against some alternative  $\theta_1$  will have poor power at alternatives “close” to  $\theta_1$ . We formalize this by deriving upper bounds on the weighted average power (WAP) of tests in a neighborhood of  $\theta_1$ , where the weights are proportional to the frequencies expected under sampling types from a

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<sup>2</sup>We note that monotonicity may be testable when combined with other assumptions. For example, there are tests of the joint assumptions of instrument monotonicity, exclusion, and independence (e.g. [Kitagawa, 2015](#)).

superpopulation (and thus concentrate around  $\theta_1$ , in terms of relative frequencies, when  $n$  is reasonably large). We show that regardless of sample size, the WAP of a size- $\alpha$  test is no greater than  $2.51\alpha$ ; thus, for a 5% test, the WAP is never more than 12.6%. The bound can be even tighter given a particular  $n$  and a lower bound on the number of defiers/compliers. For example, if  $n = 100$  and compliers and defiers are each at least 5% of the finite population, then WAP is never greater than 5.06%. We also derive upper bounds on power for unbiased tests (i.e. those with power at least  $\alpha$  for all alternatives). This upper bound converges to  $\alpha$  as  $n$  grows large, indicating that with large  $n$  all unbiased tests have nearly trivial power.

Taken together, our results suggest that frequentist tests provide limited learning about monotonicity. In particular, these tests can only be useful if we are interested in testing one particular alternative and not nearby ones. For example, with  $n = 30$  and  $n_1 = 15$ , the most powerful 5% test against any alternative rejects with probability 31% when there are 18 defiers and 12 compliers. However, this test never rejects when there are 17 defiers and 13 compliers. Our theoretical results show the low power of this test against neighboring alternatives is a generic feature of tests against monotonicity. We suspect that in most practical settings, researchers will not be interested in ultra-specific alternatives, and thus such frequentist tests will have relatively little use in practice.

From the Bayesian perspective, we show that there do exist Bayesians who update about the probability that the design-based monotonicity assumption holds, but there also exist Bayesians who never update. The existence of a Bayesian who updates follows immediately from the fact that  $\theta$  is identified. Consider a Bayesian with a two-point prior on  $\theta_0$  satisfying monotonicity and  $\theta_1$  violating monotonicity. Since  $f_{\theta_0} \neq f_{\theta_1}$ , the Bayesian updates about the probability that the null is true. However, we show that there exists a non-trivial prior  $\pi^*$  which never updates on the probability that the null hypothesis holds, i.e.  $\pi^*(\theta \in \Theta_0 \mid (Y_U, Y_T)) = \pi^*(\theta \in \Theta_0) \in (0, 1)$  for all  $Y_U, Y_T$ , where  $\Theta_0$  denotes the set of parameter values satisfying monotonicity.<sup>3</sup> Our results thus suggest that the data may be informative to *some* audience members, who are worried about particular violations of monotonicity, but there will never be consensus: some audience member is always unmoved by the data on monotonicity.

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<sup>3</sup>Note that since the likelihood is not flat,  $f_{\theta_1} \neq f_{\theta_0}$  for any  $\theta_1 \neq \theta_0$ , this Bayesian does update their posterior about  $\theta$ . However, they do not update about the event  $\theta \in \Theta_0$ .

**Related literature.** Previous work has derived the likelihood of the observed data under the design-based data-generating process we consider, in which there is a completely randomized experiment with binary outcomes, and has shown that this can be used for likelihood-based or Bayesian inference (Copas, 1973; Ding and Miratrix, 2019; Christy and Kowalski, 2025). Copas (1973) and Christy and Kowalski (2025) explicitly note that the likelihood can depend on the number of defiers  $\theta_d$ . We add to this literature an explicit analysis of identification, as well as results quantifying the extent to which a frequentist can test for monotonicity or a Bayesian updates about monotonicity.

More broadly, an extensive previous literature has considered the different implications of sampling-based versus model-based approaches to uncertainty for *inference* (e.g. Li and Ding, 2017; Abadie, Athey, Imbens and Wooldridge, 2020). This paper highlights that these different approaches can also have different implications for *identification*. We argue, however, that the classical notion of identification may be misleading in the design-based setting as a criterion for whether the data is informative about a parameter, and instead propose to evaluate the informativeness of the data through the properties of frequentist tests and Bayesian updating. Although we focus on testing monotonicity, these observations may prove useful in other design-based settings as well. Kline and Masten (2025) also study a design-based setting (although they do not consider monotonicity testing) and likewise find the textbook definition of identification inadequate, although they opt for defining alternative notions of identification rather than quantifying the scope for frequentist testing or Bayesian updating.

## 2. Setup

Consider a finite population of  $n$  individuals subjected to a completely randomized experiment with  $n_1$  treated units, where  $1 < n_1 < n$ . That is:

- (1) Each individual  $i$  has potential outcomes  $(y_i(1), y_i(0)) \in \{0, 1\}^2$ .
- (2) We observe  $(Y_i, D_i)_{i=1}^n$ , where  $Y_i = y_i(D_i)$  and  $D_i \in \{0, 1\}$ .
- (3) Fixing the finite population, randomness solely arises from the assignment of  $(D_1, \dots, D_n)$ , where

$$P[D_1 = d_1, \dots, D_n = d_n, Y_1 = y_1, \dots, Y_n = y_n] \\ = \binom{n}{n_1}^{-1} \mathbb{1} \left( \sum_{i=1}^n d_i = n_1; y_i = y_i(d_i) \text{ for all } i \right).$$

We refer to those with  $y_i(1) > y_i(0)$  as compliers,  $y_i(1) = 1 = y_i(0)$  as always-takers,  $y_i(1) < y_i(0)$  as defiers, and  $y_i(1) = 0 = y_i(0)$  as never-takers. We refer to these as the *type* of a unit. We observe the number of treated units with  $Y_i = 1$  and the number of untreated units with  $Y_i = 1$ .<sup>4</sup>

$$Y \equiv (Y_T, Y_U) = \left( \sum_{i=1}^n D_i Y_i, \sum_{i=1}^n (1 - D_i) Y_i \right).$$

The counts  $Y$  depend on the potential outcomes only through the corresponding counts of types in the finite population,

$$\theta \in \Theta \equiv \{(n_{at}, n_{nt}, n_d, n_c) \in (\mathbb{N} \cup \{0\})^4 : n_{at} + n_{nt} + n_d + n_c = n\}.$$

In particular,

$$Y_T = (\# \text{ treated always takers}) + (\# \text{ treated compliers})$$

$$Y_U = (\# \text{ untreated always takers}) + (\# \text{ untreated defiers}).$$

In a completely randomized experiment, given  $\theta = (n_{at}, n_{nt}, n_d, n_c)$ , the number of treated units of each type is distributed according to a multivariate hypergeometric distribution with parameters  $\theta$  and  $n_1$ . Let  $f_\theta(y_T, y_U)$  denote the induced probability mass function for  $(Y_T, Y_U)$  under  $\theta$ .

Sometimes, we think of the finite population as being drawn from an infinite super-population. To that end, let  $\mathcal{P} = \{(p_{at}, p_{nt}, p_d, p_c) \in [0, 1]^4 : p_{at} + p_{nt} + p_d + p_c = 1\}$  be the simplex. For an element  $p \in \mathcal{P}$ , let the corresponding distribution of  $(Y_T, Y_U)$  when unit types are drawn i.i.d. from  $\text{Multinomial}(1, p)$  be

$$g_p(y_T, y_U) = \sum_{\theta=(n_{at}, n_{nt}, n_d, n_c) \in \Theta} f_\theta(y_T, y_U) \frac{n!}{n_{at}! n_{nt}! n_c! n_d!} p_{at}^{n_{at}} p_{nt}^{n_{nt}} p_d^{n_d} p_c^{n_c}.$$

Let  $\Theta_0 = \{(n_{at}, n_{nt}, n_d, n_c) \in \Theta : \min(n_d, n_c) = 0\}$  be the set of type counts that satisfy monotonicity. Let  $\Theta_1 = \Theta \setminus \Theta_0$  be the complement. Similarly, let  $\mathcal{P}_0 = \{p \in \mathcal{P} : \min(p_d, p_c) = 0\}$  and  $\mathcal{P}_1 = \mathcal{P} \setminus \mathcal{P}_0$ .

**Remark 1** (Practical relevance of each null). Whether we prefer to test the super-population null that  $p \in \mathcal{P}_0$  or the design-based null that  $\theta_0 \in \Theta_0$  will depend on the application. If the  $n$  units are patients in a drug trial drawn randomly from a

<sup>4</sup>We note that if the researcher observes individual data, then any procedure  $\delta$  that is *anonymous*—i.e., that is invariant to permutations of the units, so that  $\delta((Y_1, D_1), \dots, (Y_n, D_n)) = \delta((Y_{\sigma(1)}, D_{\sigma(1)}), \dots, (Y_{\sigma(n)}, D_{\sigma(n)}))$  for all permutations  $\sigma : [n] \rightarrow [n]$ —is simply a function of the counts  $(Y_T, Y_U)$ . It thus suffices to restrict attention to  $(Y_T, Y_U)$  for anonymous procedures.

much larger population of patients with the same condition, then we are likely more interested in whether there are heterogeneous responses to the drug in the superpopulation of patients, and thus  $p \in \mathcal{P}_0$  is more relevant than  $\theta \in \Theta_0$ . On the other hand, if the  $n$  units are the 50 states, it may be unnatural to imagine the states as sampled from an infinite superpopulation, rendering conceptual issues for the null  $p \in \mathcal{P}_0$ . By contrast, testing  $\theta \in \Theta_0$  answers the natural question as to whether any of the 50 states have opposite-signed treatment effects. See [Copas \(1973\)](#), [Reichardt and Gollob \(1999\)](#), and [Rambachan and Roth \(2025\)](#), among others, for additional discussion of the relevance of design-based vs. superpopulation based estimands.

### 3. Identification

The typical textbook definition of identification states that a parameter is identified if two distinct values of the parameter induce different distributions of the observed data.<sup>5</sup> It is well-known that, from the superpopulation perspective, the population shares  $p$  are not point-identified ([Heckman et al., 1997](#)). In particular, any type proportion that violates monotonicity induces data that can be rationalized by some other type proportion that obeys monotonicity. By contrast, as summarized in the following result, the type counts  $\theta$  are in fact identified, and thus monotonicity violations are likewise distinguishable from  $f_\theta$ .

**Proposition 3.1.** *If  $\theta_1 \neq \theta_0 \in \Theta$ , then  $f_{\theta_1} \neq f_{\theta_0}$ , and hence the finite-population type counts  $\theta$  are identified. On the other hand, given any  $p_1 \in \mathcal{P}_1$ , there exists a  $p_0 \in \mathcal{P}_0$  such that  $g_{p_1} = g_{p_0}$ .*

**Example 1** (Illustrative example). Consider a population with 2 units, one of whom is assigned to treatment. If there is 1 always-taker and 1 never-taker ( $\theta = (1, 1, 0, 0)$ ), then  $(Y_T, Y_U)$  is either equal to  $(1, 0)$  or  $(0, 1)$ , depending on whether the always-taker is assigned to treatment or control. By contrast, if there is 1 defier and 1 complier ( $\theta = (0, 0, 1, 1)$ ), then  $(Y_T, Y_U)$  is either equal to  $(1, 1)$  or  $(0, 0)$ , depending on whether the complier is assigned to treatment or control. Thus, the distribution of the observed data differs between a population with 1 always-taker and 1 never-taker and a population with 1 complier and 1 defier, despite  $E[(Y_T, Y_U)]$  being the same. By contrast, a superpopulation with half always-takers and half never-takers and a superpopulation

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<sup>5</sup>For example, the Wikipedia page on [identifiability](#) states that a statistical model  $P_\theta$  is “identifiable if the mapping  $\theta \mapsto P_\theta$  is one-to-one.” [Lehmann and Casella \(1998, Definition 5.2\)](#) equivalently define  $\theta$  to be unidentifiable if there exist  $\theta_1 \neq \theta_2$  such that  $P_{\theta_1} = P_{\theta_2}$ .

with half compliers and half defiers would each generate the same observable data distribution for  $(Y_T, Y_U)$ , assigning equal probability to  $(0, 0)$ ,  $(0, 1)$ ,  $(1, 0)$ ,  $(1, 1)$ .

As a criterion for whether the observed data is informative of the parameter, however, the above definition of identification falls short from the design-based perspective. Two values of  $\theta$  are distinguishable in the sense that repeated draws of  $(Y_T, Y_U)$  from  $f_\theta$  would have different distributions under these two values. This, however, corresponds to knowing the distribution of outcomes from re-assigning the *same* units to *different* treatment assignments. However, in the finite population, we only observe  $(Y_T, Y_U)$  once, and thus cannot use information only learned from repeated draws. For example, knowing  $f_\theta$  implies that we know  $\text{Cov}(Y_T, Y_U)$ , yet this is difficult to learn from observing a single realization of  $f_\theta$ .

In the following sections, we consider two perspectives of evaluating whether a single realization of  $(Y_T, Y_U)$  is useful for learning about monotonicity violations. From the frequentist perspective, we consider whether one can construct tests that have non-trivial power against the null of monotonicity. From the Bayesian perspective, we consider the extent to which a Bayesian updates their prior that monotonicity holds after seeing the data.

**Remark 2.** The discussion in previous papers sometimes suggests that  $\theta$  is not identified. For example, [Ding and Miratrix \(2019\)](#) write that “Without monotonicity, the unknown parameters in the Science Table,  $(N_{11}, N_{10}, N_{01}, N_{00})$  [ $\theta$  in our notation], are no longer identifiable from the observed data.” Likewise, [Rosenbaum \(2001\)](#) writes, “The model of a nonnegative effect cannot be verified or refuted by inspecting the responses of individuals, because  $r_{Ti}$  and  $r_{Ci}$  [ $y_i(1)$  and  $y_i(0)$  in our notation] are never jointly observed on the same person.” [Proposition 3.1](#) shows that according to the usual technical definition of identification,  $\theta$  is in fact identified. The underlying intuition—that violations of monotonicity are hard to detect—is consistent with our power and updating results in the following sections, however.

#### 4. Frequentist testing

We first consider the possibility of frequentist testing against monotonicity. First, we show there exist frequentist tests with power against *some* alternatives.

**Proposition 4.1.** (Frequentist tests exist) *Suppose  $n \geq 4$  and  $n_0, n_1 \geq 2$ . Then there exist tests for monotonicity that control size and have power against some*



alternatives. That is, for any  $\alpha \in (0, 1)$  there exists a test  $\delta : \text{supp}(Y) \rightarrow [0, 1]$  such that  $\sup_{\theta_0 \in \Theta_0} E_{\theta_0}[\delta(Y)] \leq \alpha$  and  $E_{\theta_1}[\delta(Y)] > \alpha$  for some  $\theta_1 \in \Theta_1$ .<sup>6</sup>

**Intuition for tests.** Observe that in [Example 1](#), the support of  $Y$  was  $\{(0, 1), (1, 0)\}$  when there was 1 always-taker and 1 never-taker, but was  $\{(0, 0), (1, 1)\}$  when there was 1 complier and 1 defier. This illustrates that the support of  $Y$  may be different when monotonicity holds versus when it is violated. This general idea is the basis of the construction of tests for monotonicity in the proof to [Proposition 4.1](#). We show that when  $n \geq 4$ , there always exists an alternative  $\theta_1$  such that the support of  $Y$  under  $\theta_1$  does not contain the support of  $Y$  under  $\theta_0$  for any  $\theta_0$  satisfying the null: i.e.  $S_{\theta_1}^Y \not\supseteq S_{\theta_0}^Y$  for any  $\theta_0 \in \Theta_0$ , where  $S_{\theta}^Y$  is the support of  $Y$  under  $\theta$ .<sup>7</sup> It follows that a test that rejects if and only if  $Y \in S_{\theta_1}^Y$  has power of 1 to reject  $\theta_1$ , but only has size  $\alpha_0 = \sup_{\theta \in \Theta_0} E_{\theta}[1\{Y \in S_{\theta_1}^Y\}] < 1$ . We can then construct a non-trivial randomized test with arbitrary size  $\alpha \leq \alpha_0$  by rejecting with probability  $\alpha/\alpha_0 > \alpha$  when  $Y \in S_{\theta_1}^Y$ .

Although non-trivial tests against monotonicity exist from the design-based perspective, we expect their power to be poor in practice. Our next result shows that any test of monotonicity has *trivial* power against some alternatives. This implies that there are no consistent tests of monotonicity (that is, tests for which power converges to 1 for all alternatives along a sequence of finite-populations with  $n \rightarrow \infty$ ).

**Proposition 4.2.** (Trivial power for some alternative) *Every test of monotonicity has trivial power against some alternatives. That is, suppose that  $\delta : \text{supp}(Y) \rightarrow [0, 1]$  is such that  $\sup_{\theta_0 \in \Theta_0} E_{\theta_0}[\delta(Y)] \leq \alpha$  for some  $\alpha \in (0, 1)$ . Then there exists some  $\theta_1 \in \Theta_1$  such that  $E_{\theta_1}[\delta(Y)] \leq \alpha$ .*

We can further show that the lack of power is *generic* in the following sense: if we construct a test to have power against some alternative  $\theta$ , then there are alternatives “near”  $\theta$  such that power is low. More precisely, around any alternative  $\theta$ , we can define a weighting function that mimics sampling from a population with type frequencies  $p = \theta/n$ . When  $n$  is reasonably large, these weights are “concentrated” around  $\theta$  in terms of type frequencies. Weighted average power (WAP) under this weighting function turns out to never be larger than  $2.51\alpha$ , uniformly over alternatives  $\theta$ .

**Proposition 4.3.** (Low WAP) *Assume  $n \geq 4$ . Fix any  $\theta \in \Theta_1$  and let  $v = \frac{1}{n} \min(\theta_c, \theta_d) \geq 1/n$  be the size of the monotonicity violation. Let  $\vartheta \sim \text{Multinomial}(n, \theta/n)$ .*

<sup>6</sup>The proof shows that there is a non-randomized test satisfying the conditions of the proposition for  $\alpha$  sufficiently large.

<sup>7</sup>Note that this is not the case in [Example 1](#), because the support of  $Y$  when there are two always-takers is  $(1, 1) \subseteq S_{\theta_1}^Y = \{(0, 0), (1, 1)\}$ . There are thus no non-trivial tests of monotonicity with  $n_1 = n_0 = 1$ .

Consider the weight function  $w_n(\cdot; \theta)$  over  $\Theta_1$  defined by the probability mass function of  $\vartheta \mid (\vartheta \in \Theta_1)$ . Fix a test  $\delta(\cdot)$  such that  $\sup_{\theta \in \Theta_0} E_\theta[\delta(Y)] \leq \alpha$ . Then, the weighted average power around  $\theta$  is bounded,

$$\text{WAP}(\delta; \theta) \equiv \sum_{\vartheta \in \Theta_1} E_\vartheta[\delta(Y)] w_n(\vartheta; \theta) \leq \alpha \frac{1}{1 - 2(1 - v)^n + (1 - 2v)^n} \leq 2.51\alpha. \quad (1)$$

**Proposition 4.3** implies, for example, that a 5% test never has weighted average power larger than 12.6%. The bound given in **Proposition 4.3** becomes even tighter if one imposes a lower bound on the fraction of the finite population that are compliers/defiers. For example, in a population of 100, if  $\min(\theta_c, \theta_d) \geq 5$ , then the upper bound becomes 5.06%, which is virtually the same as size, uniformly over all such alternatives.

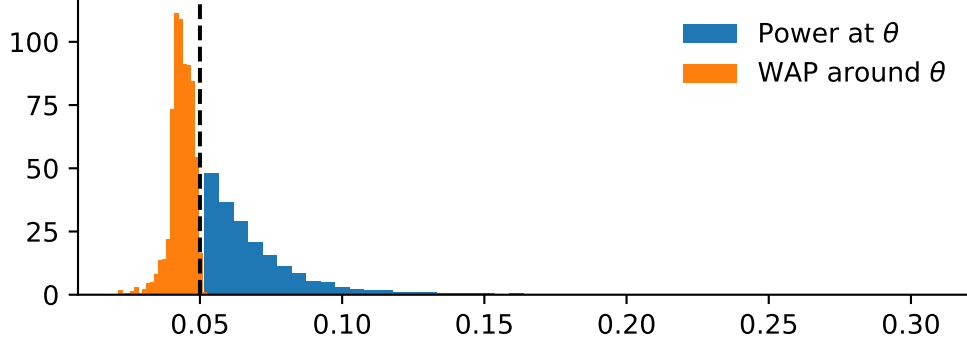
Interestingly, while we typically expect statistical power to increase with  $n$ , **Proposition 4.3** implies a *tighter* upper bound on WAP the *larger* is  $n$  (holding fixed the share of compliers and defiers). Intuitively, having a larger finite population is more similar to having an infinite superpopulation, in which case there is no testable content of monotonicity.<sup>8</sup>

**Numerical illustration with  $N = 30$ .** To illustrate these results, **Figure 1** computes the most powerful 5%-level test for every possible alternative  $\theta \in \Theta_1$ , obtained via linear programming, for  $n = 30$  and  $n_1 = 15$ . Perhaps surprisingly, all 4495 alternatives are testable, in the sense that for each alternative, there exists a test targeted to that alternative with power more than 0.05. However, the power for these tests for the targeted alternative tends to be modest: among these tests engineered to maximize power at a given alternative, only 53 of 4495 alternatives have tests with power above 0.15, and all of them have power below 0.31. These tests also tend to have very poor power for nearby alternatives, as suggested by **Proposition 4.3**: Only 18 have weighted average power above the nominal threshold 0.05, and the maximum WAP is a measly 0.0567. As a specific example, the optimal test against 18 defiers and 12 compliers achieves the maximal power of 0.31, but this test rejects with probability zero when there are 17 defiers and 13 compliers.

**Unbiased tests.** We can obtain even sharper limits on power if we restrict attention to unbiased tests. Recall that a test is unbiased if its power against all alternatives is weakly greater than its size. **Proposition 4.4** below shows that unbiased tests for monotonicity do exist (at least when  $n_1 = n_0$ ). However, **Proposition 4.5**, which is

<sup>8</sup>Similarly, the bound on WAP gets *tighter* when the violation  $v$  of the null hypothesis is *larger*.

FIGURE 1. Power of the most powerful test for a given alternative  $\theta \in \Theta_1$  for  $n = 30$ ,  $n_1 = 15$



*Notes.* We construct the most powerful 5%-test for a given alternative  $\theta$ , which we obtain via linear programming:  $\max_{\delta: \text{supp}(Y) \rightarrow [0,1]} \sum_y f_\theta(y) \delta(y)$  subjected to  $\sum_y f_\vartheta(y) \delta(y) \leq 0.05$  for all  $\vartheta \in \Theta_0$ . The blue patches show the distribution of power at  $\theta$  for each test, across all 4495 values in  $\Theta_1$ . For each test, we also compute its weighted average power (1) and show its distribution in orange.  $\square$

a consequence of [Proposition 4.3](#) above, implies that as the sample size grows large, the power of any unbiased test against any alternative becomes trivial.

**Proposition 4.4.** (Unbiased tests exist) *Suppose  $n_1 = n_0 \geq 2$ . Then there exists a non-trivial unbiased test of monotonicity: for any  $\alpha \in (0, 1)$ , there exists  $\delta : \text{supp}(Y) \rightarrow [0, 1]$  such that  $\sup_{\theta \in \Theta_0} E_\theta[\delta(Y)] \leq \alpha \leq \inf_{\theta \in \Theta_1} E_\theta[\delta(Y)]$ , with  $E_{\theta_1}[\delta(Y)] > \alpha$  for at least one  $\theta_1 \in \Theta_1$ .*

**Proposition 4.5.** (Unbiased tests have asymptotically trivial power) *Fix  $\epsilon > 0$  and  $n \geq 4$ . Fix any  $\theta \in \Theta_1$  such that  $v = \min(\theta_c, \theta_d)/n \geq \epsilon$ . Let  $\delta$  be any unbiased level- $\alpha$  test, i.e. a test satisfying  $\sup_{\theta \in \Theta_0} E_\theta[\delta(Y)] \leq \alpha \leq \inf_{\theta \in \Theta_1} E_\theta[\delta(Y)]$ . Then we have that*

$$E_\theta[\delta(Y)] \leq \alpha(1 + \eta_n(\epsilon))$$

for  $\eta_n(\epsilon) = 3.125n^{1.5}(1 - \epsilon)^n$ .

In particular, [Proposition 4.5](#) says that along any sequence of finite populations with  $v_n = \min(\theta_{c,n}, \theta_{d,n})/n \geq \epsilon$ , the power of any unbiased test is  $(1 + o(1))\alpha$  as  $n \rightarrow \infty$ .

The proof of [Proposition 4.5](#) casts the problem of maximizing  $E_\theta[\delta(Y)]$  subject to unbiasedness and size control as a linear program. The dual of this program—whereby any feasible value implies an upper bound for the power of  $\delta$ —involves choosing certain

weights over the null and the alternative. The weights  $w_n$  defined in [Proposition 4.3](#) turn out to enable a nontrivial upper bound of the primal value.

## 5. Bayesian updating

We next ask whether Bayesians update about whether  $\theta \in \Theta_0$ . The following result shows that *some* Bayesians update, but there exist Bayesians who find the data totally uninformative about whether monotonicity holds, in the sense that their posterior on  $\theta \in \Theta_0$  is equal to their prior almost surely.

**Proposition 5.1.** (Bayesian updating)

- (1) *Some Bayesians update: there exists a prior  $\pi$  with  $\pi(\Theta_0) \in (0, 1)$  such that  $\pi(\Theta_0 \mid Y) \neq \pi(\Theta_0)$  with positive  $\pi$ -probability.*
- (2) *There exist (nontrivial) Bayesian priors over  $\theta$  that never update about the probability that monotonicity holds: for any  $c \in (0, 1)$ , there exists a prior distribution  $\pi$  over  $\theta$  such that  $\pi(\theta \in \Theta_0 \mid Y) = \pi(\theta \in \Theta_0) = c$ ,  $\pi$ -almost surely.*

We note that the conclusion in part 1 that *some* Bayesian updates is rather weak. In fact, even in the superpopulation setting, there is *some* Bayesian who updates: consider, for example, the Bayesian who believes that there are defiers if and only if the average treatment effect is larger than 0.5; this Bayesian updates about the validity of monotonicity based on the information in the data about the average treatment effect. However, the updating in the design-based setting is slightly less trivial: a Bayesian in fact updates about the relative probability of two type vectors  $\theta_0, \theta_1$  that imply the same marginal distributions of  $y(0)$  and  $y(1)$  in the finite population, whereas this is not true in the superpopulation setting.

Part 2 of [Proposition 5.1](#) implies that some Bayesians do not find the data informative about whether monotonicity holds at all. Hence, the data will not be persuasive to *all* audience members. This also suggests that Bayesian inference in this setting, as considered in [Ding and Miratrix \(2019\)](#) and [Christy and Kowalski \(2025\)](#), for example, will necessarily be sensitive to the choice of prior: for the class of priors in the second part of [Proposition 5.1](#), posterior statements about monotonicity simply match the priors.

## 6. Conclusion

We study what a completely randomized experiment can reveal about finite-population monotonicity. We show that from the design-based perspective, the type shares  $\theta$  in

the finite population are in fact identified. However, the extent to which we can feasibly learn about violations of monotonicity is severely limited: frequentist tests generically have poor power, and some Bayesians never update about whether the null is true. Thus, formal identification translates to little, if any, practical learning about monotonicity. These results highlight that conclusions about identification may differ depending on whether one adopts a sampling-based versus design-based perspective, and that studying the properties of frequentist tests and Bayesian updating may provide a more realistic assessment of the extent to which learning is possible in design-based settings. An interesting avenue for future research is to explore whether similar issues arise in other design-based causal inference problems.

## Appendix A. Proofs

**Proposition 3.1.** *If  $\theta_1 \neq \theta_0 \in \Theta$ , then  $f_{\theta_1} \neq f_{\theta_0}$ , and hence the finite-population type counts  $\theta$  are identified. On the other hand, given any  $p_1 \in \mathcal{P}_1$ , there exists a  $p_0 \in \mathcal{P}_0$  such that  $g_{p_1} = g_{p_0}$ .*

*Proof.* For the first claim, it suffices to construct a mapping from  $f_\theta$  to  $\theta$ . Fix  $q = n_1/n$  as the treatment probability. Observe that, by linearity of expectation,

$$E_\theta[(Y_T, Y_U)'] = (n_{at}q + n_cq, (1-q)n_{at} + (1-q)n_d)'$$

Second, label underlying units  $i = 1, \dots, n$  and collect always takers in  $N_a \subset [n]$ , compliers in  $N_c \subset [n]$ , and defiers in  $N_d \subset [n]$ . Let  $N_1 \subset [n]$  collect the (random) set of treated individuals. Observe that

$$\begin{aligned} E_\theta[Y_T Y_U] &= \sum_{i \neq j, i \in N_a \cup N_c, j \in N_a \cup N_d} P(i \in N_1, j \notin N_1) && \text{(Linearity of expectations)} \\ &= |\{(i, j) : i \neq j, i \in N_a \cup N_c, j \in N_a \cup N_d\}| \cdot P(1 \in N_1, 2 \notin N_1) \\ & && \text{(Symmetry)} \\ &= [(n_{at} + n_c)(n_{at} + n_d) - n_a] P(1 \in N_1, 2 \notin N_1). \end{aligned}$$

Thus,

$$(n_{at} + n_c)(n_{at} + n_d) - n_{at} = \frac{E_\theta[Y_T Y_U]}{P(1 \in N_1, 2 \notin N_1)}$$

is a function of  $f_\theta$ . Letting  $(\mu_T, \mu_Y, \mu_{TU}) := (E_\theta[Y_T], E_\theta[Y_U], E_\theta[Y_T Y_U])$ , we see that

$$\frac{\mu_T}{q} = n_{at} + n_c, \quad \frac{\mu_U}{1-q} = n_{at} + n_d, \quad \mu_{TU} = \frac{\mu_T}{q} \frac{\mu_U}{1-q} - n_{at}.$$

It follows that

$$n_{at} = \mu_{TU} - \frac{\mu_T}{q} \frac{\mu_U}{1-q}, \quad n_c = \frac{\mu_T}{q} - n_{at}, \quad n_d = \frac{\mu_U}{1-q} - n_{at}.$$

Since  $(\mu_T, \mu_Y, \mu_{TU})$  is a function of  $f_\theta$ , we have therefore shown that there is an inverse mapping from  $f_\theta$  to  $\theta$ , and hence the mapping  $\theta \mapsto f_\theta$  must be one-to-one, as needed.

For the second claim, observe that the superpopulation data-generating process can be represented as:

- (1) Fix index  $i = 1, \dots, n$ . The first  $n_1$  units are treated.
- (2) For each unit  $i$ , sample her type from  $\text{Multinomial}(1, p)$ .
- (3) The counts  $Y$  are then functions of type counts in the first  $n_1$  units and the next  $n - n_1$  units.

We can check that under this process,  $\theta \sim \text{Multinomial}(n, p)$  and  $Y \mid \theta \sim f_\theta$ . But under this process, we have that  $Y_T \sim \text{Bin}(n_1, p_{at} + p_c)$  and  $Y_U \sim \text{Bin}(n - n_1, p_{at} + p_d)$ , and  $Y_T \perp\!\!\!\perp Y_U$ . We thus see that the unconditional distribution of  $Y$  depends on  $p$  only through the sums  $p_{at} + p_c$  and  $p_{at} + p_d$ . (Copas (1973, p. 472-3) likewise shows that the likelihood depends only on these sums.) For any given  $p \in \mathcal{P}_1$ , observe that  $p'$  defined by

$$p'_{at} = p_{at} + \min(p_c, p_d) \quad p'_c = p_c - \min(p_c, p_d) \quad p'_d = p_d - \min(p_c, p_d) \quad p'_{nt} = p_{nt} + \min(p_c, p_d)$$

generates observationally equivalent  $(Y_T, Y_U)$ . However,  $\min(p'_c, p'_d) = 0$  and thus  $p' \in \mathcal{P}_0$ .  $\square$

**Lemma A.1.** Suppose  $n_1 = \frac{n}{2} = n_0$ . Then there exist priors  $\pi_A$  and  $\pi_B$  on  $\theta$  such that  $\pi_A(\theta \in \Theta_0) = 1$ ,  $\pi_B(\theta \in \Theta_0) = 0$ , and  $\pi_A(Y = y) = \pi_B(Y = y)$  for all  $y \in \{0, \dots, n_1\} \times \{0, \dots, n_0\}$ .

*Proof.* Let  $\tilde{\pi}_p$  denote the multinomial prior on  $(n_{at}, n_{nt}, n_d, n_c)$  with probabilities  $p = (p_{at}, p_{nt}, p_d, p_c)$ . That is,

$$(n_{at}, n_{nt}, n_d, n_c) \sim \tilde{\pi}_p \sim \text{Multinomial}(n, p).$$

Define  $\tilde{\pi}_A = \tilde{\pi}_{(0.5, 0.5, 0, 0)}$  and  $\tilde{\pi}_B = \tilde{\pi}_{(0, 0, 0.5, 0.5)}$ . The prior  $\tilde{\pi}_A$  arises from assuming that the units in the finite population were sampled i.i.d. from a superpopulation in which half of individuals are always-takers and the other half are never-takers. The prior  $\tilde{\pi}_B$  arises analogously if the superpopulation is half compliers and half defiers. As argued in the proof to Proposition 3.1, the marginal distribution of  $Y$  after (i) sampling  $\theta \sim \text{Multinomial}(1, p)$  and (ii) generating  $Y \sim f_\theta$  depends on  $p$  only through  $p_{at} + p_c$  and  $p_{at} + p_d$ . It follows that the two priors imply the same unconditional distribution for  $Y$ ,  $\tilde{\pi}_A(Y) = \tilde{\pi}_B(Y)$  for all  $Y$ .

Now, consider type counts  $\theta_0(n_{at}) = (n_{at}, n - n_{at}, 0, 0)$ , which have positive numbers of only always-takers and never-takers. Observe that the support of  $Y$  under  $\theta_0$  is all points of the form  $(m, n_{at} - m)$  for  $m = \max\{0, n_{at} - n_0\}, \dots, \min\{n_1, n_{at}\}$ , where  $(m, n_{at} - m)$  is the realization of  $Y$  if  $m$  of the always-takers are selected for treatment. Hence the support points for  $Y$  under  $\theta_0$  lie on a line with slope of  $-1$  and intercept  $n_{at}$ . Letting  $S_{\theta_0}^Y$  denote the support of  $Y$  under  $\theta_0$ , we see that the  $S_{\theta_0}^Y$  are disjoint for all  $\theta_0$  to which  $\tilde{\pi}_A$  assigns positive support:

$$S_{\theta_0(n_{at})}^Y \cap S_{\theta_0(n'_{at})}^Y = \emptyset \text{ for } n_{at} \neq n'_{at}.$$

Hence, for any set  $\tilde{\Theta}_0$  of the form  $\{\theta_0(n_{at,1}), \dots, \theta_0(n_{at,K})\}$ , we have that

$$\tilde{\pi}_A(Y = y \mid \theta \in \tilde{\Theta}_0) = \tilde{\pi}_A(Y = y \mid Y \in S_{\tilde{\Theta}_0}^Y),$$

for  $S_{\tilde{\Theta}_0} = \bigcup_{\theta_0 \in \tilde{\Theta}_0} S_{\theta_0}^Y$ .

Similarly, let  $\theta_1(n_c) = (0, 0, n - n_c, n_c)$ , which has only compliers and defiers. The support points of  $Y$  under  $\theta_1$  take the form  $(m, n_0 - (n_c - m)) = (m, m + n_0 - n_c)$  for  $m = \max\{0, n_c - n_0\}, \dots, \min\{n_1, n_c\}$ , corresponding to the case where  $m$  compliers are selected for treatment. These points lie on an upward sloping line with slope 1 and intercept  $n_0 - n_c$ . Letting  $S_{\theta_1}^Y$  denote the support of  $Y$  under  $\theta_1$ , we again see that the  $S_{\theta_1}^Y$  are disjoint. Hence, for any set  $\tilde{\Theta}_1$  of the form  $\{\theta_1(n_{c,1}), \dots, \theta_1(n_{c,K})\}$ , we have that

$$\tilde{\pi}_B(Y = y \mid \theta \in \tilde{\Theta}_1) = \tilde{\pi}_B(Y = y \mid Y \in S_{\tilde{\Theta}_1}^Y),$$

for  $S_{\tilde{\Theta}_1} = \bigcup_{\theta_1 \in \tilde{\Theta}_1} S_{\theta_1}^Y$ .

Now, let

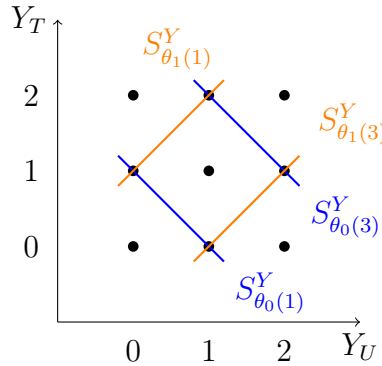
$$\tilde{\Theta}_0 = \begin{cases} \{\theta_0(n_{at}) \mid n_{at} = 0, 2, \dots, n\} & n_1 \text{ is odd} \\ \{\theta_0(n_{at}) \mid n_{at} = 1, 3, \dots, n-1\} & n_1 \text{ is even} \end{cases} \subset \Theta_0$$

and  $\tilde{\Theta}_1 = \{\theta_1(n_c) \mid n_d = 1, 3, \dots, n-1\} \subset \Theta_1$ . [Lemma A.2](#) shows formally that

$$S_{\tilde{\Theta}_1}^Y = S_{\tilde{\Theta}_0}^Y.$$

An intuitive illustration of the proof is shown in [Figure 2](#) for the setting where  $n = 4$ , in which case  $S_{\tilde{\Theta}_1}$  corresponds to the union of the points on the two upward-sloping lines in orange, and  $S_{\tilde{\Theta}_0}$  corresponds to the unions of the points on the two downward-sloping lines in blue.

FIGURE 2. Illustration of the sets  $S_{\tilde{\Theta}_0}$  and  $S_{\tilde{\Theta}_1}$





Define  $\pi_A(\theta) := \tilde{\pi}_A(\theta \mid \theta \in \tilde{\Theta}_0)$  and  $\pi_B(\theta) := \tilde{\pi}_B(\theta \mid \theta \in \tilde{\Theta}_1)$ . It is immediate that  $\pi_A(\theta \in \Theta_0) = 1$  and  $\pi_B(\theta \in \Theta_1) = 1$  by construction. Further, we have shown that

$$\pi_A(Y = y) = \tilde{\pi}_A(Y = y \mid Y \in S_{\tilde{\Theta}_0}^Y) = \tilde{\pi}_B(Y = y \mid Y \in S_{\tilde{\Theta}_1}^Y) = \pi_B(Y = y).$$

This completes the proof.  $\square$

**Lemma A.2.** *Fix an even  $n$  and let  $n_1 = n_0 = n/2$ . Let*

$$B = \{(m, n_0 - (n_c - m)) : m = \max(0, n_c - n_0), \dots, \min(n_1, n_c), n_c = 1, 3, 5, \dots, n - 1\}$$

and

$$A = \left\{ (m, n_a - m) : m = \max(0, n_a - n_0), \dots, \min(n_1, n_a), n_a = \begin{cases} 1, 3, \dots, n - 1 & n/2 \text{ is even} \\ 0, 2, \dots, n & n/2 \text{ is odd} \end{cases} \right\}.$$

Then

$$A = B = \left\{ (a, b) \in [n/2] \times [n/2] : \begin{cases} \text{parities of } a, b \text{ are different} & n/2 \text{ is even} \\ \text{parities of } a, b \text{ are the same} & n/2 \text{ is odd} \end{cases} \right\} \equiv C$$

*Proof.* It is easy to see that  $A$  and  $B$  are both subsets of  $[n/2] \times [n/2]$ . Observe that  $B$  consists of opposite-parity  $(a, b)$  if  $n_0$  is even and consists of same-parity points if  $n_0$  is odd. Therefore  $B \subset C$ . Similarly,  $A$  consists of opposite-parity points if  $n/2$  is even and same-parity points if  $n/2$  is odd. Therefore  $A \subset C$ .

Now, suppose  $n/2$  is even and consider  $(a, b) \in [n/2] \times [n/2]$  of opposite parity. Let  $n_a = a + b$  and  $m = a$ . Then  $(m, n_a - m) \in A$ , since  $n_a$  is odd and bounded by  $n$ . Similarly, let  $m = a$  and  $n_c = m + n_0 - b$ . Since  $n_c$  is odd and  $0 \leq n_c \leq n$ , we conclude that  $(a, b) \in B$  as well. This proves that  $A = B = C$  when  $n/2$  is even. The proof for  $A = B = C$  when  $n/2$  is odd is analogous.  $\square$

**Proposition 4.2.** (Trivial power for some alternative) *Every test of monotonicity has trivial power against some alternatives. That is, suppose that  $\delta : \text{supp}(Y) \rightarrow [0, 1]$  is such that  $\sup_{\theta_0 \in \Theta_0} E_{\theta_0}[\delta(Y)] \leq \alpha$  for some  $\alpha \in (0, 1)$ . Then there exists some  $\theta_1 \in \Theta_1$  such that  $E_{\theta_1}[\delta(Y)] \leq \alpha$ .*

*Proof.* By Lemma A.1, there exists priors  $\pi_A$  and  $\pi_B$  such that  $\pi_A(\theta \in \Theta_0) = 1$ ,  $\pi_B(\theta \in \Theta_1)$ , and  $\pi_A(Y = y) = \pi_B(Y = y)$  for all  $y$ . Observe that

$$E_{\theta \sim \pi_A}[\delta(Y)] = E_{\theta \sim \pi_A} \left[ \underbrace{E_{\theta}[\delta(Y)]}_{\leq \alpha \text{ since } \theta \in \Theta_0} \right] \leq \alpha,$$

where the first equality uses the law of iterated expectations, and the second the assumption that  $E_\theta[\delta(Y)] \leq \alpha$  for all  $\theta \in \Theta_0$ . However, since  $\pi_A(Y = y) = \pi_B(Y = y)$  for all  $y$ , it follows that

$$E_{\theta \sim \pi_B}[\delta(Y)] = E_{\theta \sim \pi_A}[\delta(Y)] \leq \alpha$$

and hence

$$E_{\theta \sim \pi_B}[\delta(Y)] = E_{\theta \sim \pi_B}[E_\theta[\delta(Y)]] \leq \alpha.$$

It follows that there exists some  $\theta_1 \in \text{supp}(\pi_B) \subseteq \Theta_1$  such that  $E_{\theta_1}[\delta(Y)] \leq \alpha$ , which gives the desired result.  $\square$

**Proposition 4.1.** (Frequentist tests exist) *Suppose  $n \geq 4$  and  $n_0, n_1 \geq 2$ . Then there exist tests for monotonicity that control size and have power against some alternatives. That is, for any  $\alpha \in (0, 1)$  there exists a test  $\delta : \text{supp}(Y) \rightarrow [0, 1]$  such that  $\sup_{\theta_0 \in \Theta_0} E_\theta[\delta(Y)] \leq \alpha$  and  $E_{\theta_1}[\delta(Y)] > \alpha$  for some  $\theta_1 \in \Theta_1$ .<sup>9</sup>*

*Proof.* Suppose, without loss of generality, that  $n_1 \leq n_0$  (if not, we can adopt the same argument reversing the roles of  $n_d$  and  $n_c$ ). Let  $\theta_1$  be the type with  $n_d = n_1 - 1$ ,  $n_c = n - n_d$ , and  $n_{at} = n_{nt} = 0$ . Note that  $n_c = n - n_1 + 1 \geq 2$ . Observe that under  $\theta = \theta_1$ , the support of  $Y$  is

$$S_{\theta_1}^Y = \{(m, n_d - (n_1 - m)) : m = 1, \dots, \min\{n_1, n_c\}\},$$

with  $(m, n_d - (n_1 - m))$  corresponding to the realization of  $Y$  when  $m$  compliers are assigned to treatment. Observe that the points in  $S_{\theta_1}^Y$  lie on an upward sloping line with slope of 1. That is, for any  $y = (y_1, y_0)$  and  $y' = (y'_1, y'_0)$  both in  $S_{\theta_1}^Y$ , we have that  $y - y' = c \cdot (1, 1)$ .

Now, for any  $\theta_0 \in \Theta_0$ , let  $S_{\theta_0}^Y$  denote the support of  $Y$  under  $\theta = \theta_0$ . We claim that  $S_{\theta_0}^Y \not\subseteq S_{\theta_1}^Y$  for all  $\theta_0 \in \Theta_0$ .

Case 1 Suppose that  $\theta_0$  corresponds to there only being one type in the population.

Then  $S_{\theta_0}^Y$  is a singleton set with element either  $(0, 0)$ ,  $(n_1, 0)$ ,  $(n_1, n_0)$  depending on whether the lone type is NT, C, or AT. It is clear that  $(0, 0) \notin S_{\theta_1}^Y$ . Next, note that the only possible element of  $S_{\theta_1}^Y$  with first element equal to  $n_1$  is  $(n_1, n_d)$ , corresponding to the case where  $m = n_1 = \min\{n_1, n_c\}$ . However, by construction we have that  $0 < n_d = n_1 - 1 < n_0$ , and thus  $(n_1, n_d) \neq (n_1, 0)$  and  $(n_1, n_d) \neq (n_1, n_0)$ .

<sup>9</sup>The proof shows that there is a non-randomized test satisfying the conditions of the proposition for  $\alpha$  sufficiently large.

Case 2 Suppose  $\theta_0 \in \Theta_0$  that has positive numbers of at least two types. Suppose towards contradiction that  $S_{\theta_0}^Y \subseteq S_{\theta_1}^Y$ . Consider any support point  $(y_1, y_0)$  in  $S_{\theta_0}^Y$ . Note that  $(y_1, y_0) = (\sum_i D_i y_i(1), \sum_i (1 - D_i) y_i(0))$  for some choice of  $D_i$  and a population such that  $\{(y_i(1), y_i(0))\}_{i=1}^n$  has the types with frequencies given by  $\theta_0$ . Since there are at least two types under  $\theta_0$ , there are distinct indices  $j, k$  such that  $D_j = 1, D_k = 0$  and individuals  $j$  and  $k$  are of different types, i.e.  $(y_j(0), y_j(1)) \neq (y_k(0), y_k(1))$ . Now consider the treatment assignment  $\tilde{D}$  that swaps the treatment assignments of units  $j$  and  $k$  and leaves the other assignments unchanged, i.e.  $\tilde{D}_j = 0, \tilde{D}_k = 1$ , and  $\tilde{D}_i = D_i$  for  $i \notin \{j, k\}$ . The realized outcome under treatment assignment  $\tilde{D}$  is  $(y'_1, y'_0) = (\sum_i \tilde{D}_i y_i(1), \sum_i (1 - \tilde{D}_i) y_i(0))$ , and thus  $(y'_1, y'_0) \in S_{\theta_0}^Y \subseteq S_{\theta_1}^Y$ . However, we have that

$$(y'_1, y'_0) - (y_1, y_0) = (y_k(1) - y_j(1), y_j(0) - y_k(0)).$$

Note that since  $(y_j(0), y_j(1)) \neq (y_k(0), y_k(1))$ , it follows that  $(y'_1, y'_0) - (y_1, y_0) \neq 0$ . Then since  $(y_1, y_0), (y'_1, y'_0) \in S_{\theta_1}^Y$ , it must be the case that  $(y'_1, y'_0) - (y_1, y_0) = c \cdot (1, 1)$  for an integer  $c \neq 0$ . It follows that

$$\begin{aligned} y_k(1) - y_j(1) &= c \\ y_j(0) - y_k(0) &= c. \end{aligned}$$

Adding the two equations, we obtain that

$$(y_k(1) - y_k(0)) - (y_j(1) - y_j(0)) = 2c \neq 0.$$

Since the treatment effects  $(y_k(1) - y_k(0))$  and  $(y_j(1) - y_j(0))$  are each in  $\{-1, 0, 1\}$ , their difference can equal an even non-zero integer only if one is equal to 1 and the other is equal to  $-1$ . However, this contradicts  $\theta_0$  satisfying monotonicity. It follows that  $S_{\theta_1}^Y \not\subseteq S_{\theta_0}^Y$ , as we wished to show.

Now, let  $\delta^*(Y) = 1\{Y \in S_{\theta_1}^Y\}$ . Since  $S_{\theta_1}^Y \not\subseteq S_{\theta_0}^Y$  for all  $\theta_0 \in \Theta_0$ , it follows that  $E_{\theta_0}[\delta^*(Y)] < 1$  for all  $\theta_0 \in \Theta_0$ . Since  $\Theta_0$  is finite, we thus obtain that  $\sup_{\theta_0 \in \Theta_0} E_{\theta_0}[\delta^*(Y)] < 1$ . However, by construction  $E_{\theta_1}[\delta^*(Y)] = 1$ . Hence,  $\delta^*(Y)$  controls size at level  $\alpha^* = \sup_{\theta_0 \in \Theta_0} E_{\theta_0}[\delta^*(Y)] < 1$  and has power of 1 against the alternative  $\theta_1$ . If  $\alpha^* < \alpha$ , then the proof is complete by setting  $\delta(Y) = \delta^*(Y)$  (and thus we have a non-randomized test). If  $\alpha^* > \alpha$ , set  $\delta(Y) = \frac{\alpha}{\alpha^*} \delta^*(Y)$ . Then by construction  $\sup_{\theta_0 \in \Theta_0} E_{\theta_0}[\delta(Y)] = \alpha$  and  $E_{\theta_1}[\delta(Y)] = \alpha^* > \alpha$ .  $\square$

**Proposition 4.3.** (Low WAP) Assume  $n \geq 4$ . Fix any  $\theta \in \Theta_1$  and let  $v = \frac{1}{n} \min(\theta_c, \theta_d) \geq 1/n$  be the size of the monotonicity violation. Let  $\vartheta \sim \text{Multinomial}(n, \theta/n)$ . Consider the weight function  $w_n(\cdot; \theta)$  over  $\Theta_1$  defined by the probability mass function of  $\vartheta \mid (\vartheta \in \Theta_1)$ . Fix a test  $\delta(\cdot)$  such that  $\sup_{\theta \in \Theta_0} E_\theta[\delta(Y)] \leq \alpha$ . Then, the weighted average power around  $\theta$  is bounded,

$$\text{WAP}(\delta; \theta) \equiv \sum_{\vartheta \in \Theta_1} E_\vartheta[\delta(Y)] w_n(\vartheta; \theta) \leq \alpha \frac{1}{1 - 2(1 - v)^n + (1 - 2v)^n} \leq 2.51\alpha. \quad (1)$$

*Proof.* Let  $\pi(t; \theta)$  be the PMF for  $\text{Multinomial}(n, \theta/n)$ . Then

$$w_n(t; \theta) = \frac{\pi(t; \theta)}{\sum_{t \in \Theta_1} \pi(t; \theta)} \mathbb{1}(t \in \Theta_1).$$

Define  $g_\theta(y) = \sum_{t \in \Theta_0 \cup \Theta_1} f_t(y) \pi(t; \theta)$ . By [Proposition 3.1](#), there exists some  $p \in \mathcal{P}_0$  such that  $g_\theta(y) = g_p(y)$ . We thus have the following expansion of WAP,

$$\begin{aligned} \text{WAP}(\delta; \theta) &= \sum_{t \in \Theta_0 \cup \Theta_1} \sum_y \delta(y) f_t(y) \frac{\pi(t; \theta)}{\sum_{t \in \Theta_1} \pi(t; \theta)} \mathbb{1}(t \in \Theta_1) \\ &= \underbrace{\left( \sum_{t \in \Theta_1} \pi(t; \theta) \right)^{-1}}_{\equiv Z_1^{-1}} \sum_y \delta(y) \left[ \sum_{t \in \Theta_0 \cup \Theta_1} f_t(y) \pi(t; \theta) - \sum_{t \in \Theta_0} f_t(y) \pi(t; \theta) \right] \\ &= \frac{1}{Z_1} \left[ E_{g_\theta}[\delta(Y)] - \sum_{t \in \Theta_0} E_t[\delta(Y)] \pi(t; \theta) \right] \\ &\leq \frac{1}{Z_1} E_{g_p}[\delta(Y)] \\ &\leq \frac{\alpha}{Z_1} \quad (\delta \text{ controls size}) \end{aligned}$$

Let  $q = \theta/n$ . Note that

$$Z_1 = 1 - P_{V \sim \text{Multinomial}(n, q)}(\min(V_c, V_d) = 0) = 1 - [(1 - q_c)^n + (1 - q_d)^n - (1 - q_c - q_d)^n].$$

It is easy to check that  $Z_1$  is increasing in  $q_c$  and  $q_d$ , thus it is lower bounded:

$$Z_1 \geq 1 - 2(1 - v)^n + (1 - 2v)^n,$$

where recall  $v = \frac{1}{n} \min\{\theta_c, \theta_d\} = \min\{q_c, q_d\}$ . This proves the first inequality. The second inequality follows from examining that  $v \geq 1/n$  and that

$$\frac{1}{1 - 2(1 - 1/n)^n + (1 - 2/n)^n} \leq 2.51 \text{ for all } n > 3.$$

□

**Proposition 4.4.** (Unbiased tests exist) *Suppose  $n_1 = n_0 \geq 2$ . Then there exists a non-trivial unbiased test of monotonicity: for any  $\alpha \in (0, 1)$ , there exists  $\delta : \text{supp}(Y) \rightarrow [0, 1]$  such that  $\sup_{\theta \in \Theta_0} E_\theta[\delta(Y)] \leq \alpha \leq \inf_{\theta \in \Theta_1} E_\theta[\delta(Y)]$ , with  $E_{\theta_1}[\delta(Y)] > \alpha$  for at least one  $\theta_1 \in \Theta_1$ .*

*Proof.* Let  $\delta_0(Y) = \alpha \cdot 1\{(Y_T, Y_U) \notin \{(n_1, 0), (0, n_0)\}\}$  be the test that rejects with probability 0 if  $Y$  is either  $(n_1, 0)$  or  $(0, n_0)$ , and rejects with probability  $\alpha$  otherwise. Let  $S_\theta^Y$  be the support of  $Y$  under parameter  $\theta$ . Note that by construction, for any  $\theta_0 \in \Theta_0$ , we have that

$$\begin{aligned} E_{\theta_0}[\delta_0(Y)] &< \alpha \text{ if } S_{\theta_0}^Y \cap \{(n_1, 0), (0, n_0)\} \neq \emptyset, \\ E_{\theta_0}[\delta_0(Y)] &= \alpha \text{ if } S_{\theta_0}^Y \cap \{(n_1, 0), (0, n_0)\} = \emptyset. \end{aligned}$$

Now, we claim that if  $(n_1 - 1, 1) \in S_{\theta_0}^Y$  for  $\theta_0 \in \Theta_0$ , then

$$S_{\theta_0}^Y \cap \{(n_1, 0), (0, n_0)\} \neq \emptyset.$$

To see this, suppose first that  $\theta_0$  has  $n_d = 0$ . Then  $y_i(1) \geq y_i(0)$  for all  $i = 1, \dots, n$ . If there exists a treatment allocation  $D$  such that  $Y(D) = (n_1 - 1, 1)$ , then there exists one  $i$  for whom  $(Y_i, D_i) = (1, 0)$ . It follows that  $y_i(0) = 1$  and hence  $y_i(1) = 1$ . Likewise, there must be one  $j$  for whom  $(Y_j, D_j) = (0, 1)$ , which implies that  $Y_j(1) = 0$  and hence  $Y_j(0) = 0$ . Letting  $\tilde{D}$  be the treatment allocation that swaps the assignments of  $i$  and  $j$  and otherwise preserves the allocation of  $D$ , we see that

$$Y(\tilde{D}) = Y(D) + (1, -1) = (n_1, 0).$$

We have thus shown that  $(n_1, 0) \in S_{\theta_0}^Y$ .

Similarly, suppose that  $\theta_0$  has  $n_c = 0$ . Then  $y_i(1) \leq y_i(0)$  for  $i = 1, \dots, n$ . If there exists a treatment allocation  $D$  such that  $Y(D) = (n_1 - 1, 1)$ , then there exists a set  $A \subset [n]$  of size  $n_1 - 1$  such that all  $i \in A$  have  $(Y_i, D_i) = (1, 1)$ , which implies that  $y_i(1) = 1$  and hence  $y_i(0) = 1$ . Likewise, there exists a set  $B \subset [n]$  of size  $n_0 - 1 = n_1 - 1$  such that for all  $j \in B$ ,  $(Y_j, D_j) = (0, 0)$ , which implies that  $Y_j(0) = 0$  and hence  $Y_j(1) = 0$ . Letting  $\tilde{D}$  be the treatment allocation that swaps the treatment assignments of units in  $A$  and  $B$ , we see that

$$Y(\tilde{D}) = Y(D) + (-(n_1 - 1), n_1 - 1) = (0, n_1) = (0, n_0),$$

and hence  $(0, n_0) \in S_{\theta_0}^Y$ . This completes the proof that

$$S_{\theta_0}^Y \cap \{(n_1, 0), (0, n_0)\} \neq \emptyset.$$

Now, let  $\delta_1(Y) = 1\{(Y_T, Y_U) = (n_1 - 1, 1)\}$  be the test that rejects if  $Y$  is  $(n_1 - 1, 1)$ . The argument above implies that for all  $\theta_0 \in \Theta_0$ ,

$$E_{\theta_0}[\delta_0(Y)] < \alpha \text{ if } E_{\theta_0}[\delta_1(Y)] > 0,$$

$$E_{\theta_0}[\delta_0(Y)] = \alpha \text{ if } E_{\theta_0}[\delta_1(Y)] = 0.$$

Since  $\Theta_0$  is finite, it follows that there exists  $\epsilon > 0$  such that, for

$$\delta(Y) = \delta_0(Y) + \epsilon \delta_1(Y),$$

we have  $E_{\theta_0}[\delta(Y)] \leq \alpha$  for all  $\theta_0 \in \Theta_0$ .

Next, we claim that  $E_{\theta_1}[\delta(Y)] \geq \alpha$  for all  $\theta_1 \in \Theta_1$ . Since

$$E_{\theta_1}[\delta(Y)] \geq E_{\theta_1}[\delta_0(Y)] = \alpha P_{\theta_1}(Y \notin \{(n_1, 0), (0, n_0)\}),$$

it suffices to show that

$$S_{\theta_1}^Y \cap \{(n_1, 0), (0, n_0)\} = \emptyset,$$

in which case  $E_{\theta_1}[\delta_0(Y)] = \alpha$ . To show this, we prove the contrapositive: if  $S_{\theta}^Y$  contains  $(n_1, 0)$  or  $(0, n_0)$ , then  $\theta \in \Theta_0$ . Indeed, if there is a treatment allocation with  $(Y_T, Y_U) = (n_1, 0)$ , then all  $n_1$  treated units must be always-takers or compliers, and all  $n_0$  control units must be never-takers or compliers, and thus there can be no defiers. Analogously, if there is a treatment allocation with  $(Y_T, Y_U) = (0, n_0)$ , then all treated units must be never-takers or defiers, and all control units must be always-takers or defiers, and thus there are no compliers.

Finally, we show that there exists  $\theta_1$  such that  $E_{\theta_1}[\delta(Y)] > \alpha$ . Since we showed above that  $E_{\theta_1}[\delta_0(Y)] = \alpha$  for all  $\theta_1 \in \Theta_1$ , it suffices to show that there exists some  $\theta_1 \in \Theta_1$  such that  $E_{\theta_1}[\delta_1(Y)] > 0$ , or equivalently  $P_{\theta_1}(Y = (n_1 - 1, 1)) > 0$ . However, if  $\theta_1$  corresponds to  $(n_{at}, n_{nt}, n_d, n_c) = (0, 0, 1, n - 1)$ , then  $Y = (n_1 - 1, 1)$  obtains when the defer is assigned to control.  $\square$

**Proposition 4.5.** (Unbiased tests have asymptotically trivial power) *Fix  $\epsilon > 0$  and  $n \geq 4$ . Fix any  $\theta \in \Theta_1$  such that  $v = \min(\theta_c, \theta_d)/n \geq \epsilon$ . Let  $\delta$  be any unbiased level- $\alpha$  test, i.e. a test satisfying  $\sup_{\theta \in \Theta_0} E_{\theta}[\delta(Y)] \leq \alpha \leq \inf_{\theta \in \Theta_1} E_{\theta}[\delta(Y)]$ . Then we have that*

$$E_{\theta}[\delta(Y)] \leq \alpha(1 + \eta_n(\epsilon))$$

for  $\eta_n(\epsilon) = 3.125n^{1.5}(1 - \epsilon)^n$ .

*Proof.* The maximum power at  $\theta$  for  $\delta$  is defined by the following linear program:

$$\begin{aligned} E_\theta[\delta(Y)] &\leq \max_{\delta} \sum_y f_\theta(y) \delta(y) \text{ subject to} \\ \sum_y f_t(y) \delta(y) &\leq \alpha \forall t \in \Theta_0 \\ \sum_y f_t(y) \delta(y) &\geq \alpha \forall t \in \Theta_1 \\ \delta(y) &\in [0, 1]. \end{aligned}$$

The dual program is

$$\min_{\lambda(t) \geq 0, \mu(t) \geq 0} \alpha \left[ \sum_{t \in \Theta_0} \lambda(t) - \sum_{t \in \Theta_1} \mu(t) \right] + \sum_y \left[ f_\theta(y) - \sum_{t \in \Theta_0} \lambda(t) f_t(y) + \sum_{t \in \Theta_1} \mu(t) f_t(y) \right]_+.$$

Thus, any dual feasible  $\lambda, \mu$  implies an upper bound for  $E_\theta[\delta(Y)]$ .

Let  $p_1 = \theta/n \in \mathcal{P}_1$  and let  $\pi(t; p_1)$  be the PMF for Multinomial( $n, p_1$ ). Note that  $\pi(\theta; p_1) > 0$  and define  $c = \frac{1}{\pi(\theta; p_1)}$ . Define, over all of  $\Theta_0 \cup \Theta_1$ ,

$$\mu(t) = \begin{cases} c\pi(t; p_1), & t \neq \theta \\ 0 & t = \theta \end{cases}$$

Then

$$\sum_{t \in \Theta_1} \mu(t) f_t(y) + f_\theta(y) \leq \sum_{t \in \Theta_1 \cup \Theta_0} \mu(t) f_t(y) + f_\theta(y) = cg_{p_1}(y) = cg_{p_0}(y)$$

for some  $p_0 \in \mathcal{P}_0$  by [Proposition 3.1](#). Define

$$\lambda(t) = c\pi(t; p_0) \implies \sum_{t \in \Theta_0} \lambda(t) f_t(y) = cg_{p_0}(y).$$

With this choice of  $\lambda, \mu$ ,

$$\left[ f_\theta(y) - \sum_{t \in \Theta_0} \lambda(t) f_t(y) + \sum_{t \in \Theta_1} \mu(t) f_t(y) \right]_+ = 0.$$

Now,

$$\sum_{t \in \Theta_0} \lambda(t) - \sum_{t \in \Theta_1} \mu(t) = c - \left[ c - 1 - c \sum_{t \in \Theta_0} \pi(t; p_1) \right] = 1 + \frac{\pi(\Theta_0; p_1)}{\pi(\theta; p_1)}.$$

Thus

$$E_\theta[\delta(Y)] \leq \alpha \left( 1 + \frac{\pi(\Theta_0; p_1)}{\pi(\theta; p_1)} \right)$$

By the argument in the proof of [Proposition 4.3](#),

$$\pi(\Theta_0; p_1) \leq 2(1 - v)^n - (1 - 2v)^n \leq 2(1 - \epsilon)^n.$$

Meanwhile,

$$\pi(\theta; p_1) = \frac{n!}{\theta_{at}! \theta_{nt}! \theta_c! \theta_d!} p_{1at}^{\theta_{at}} p_{1nt}^{\theta_{nt}} p_{1c}^{\theta_c} p_{1d}^{\theta_d}$$

Let  $m \in \{2, 3, 4\}$  be the number of entries in  $\theta$  that are positive. Stirling's formula implies the bounds ([Robbins, 1955](#)):

$$\sqrt{2\pi} k^{k+1/2} e^{-k} \leq k! \leq e k^{k+1/2} e^{-k}$$

for all integer  $k \geq 1$ . Plug in these bounds with  $p_1 = \theta/n$  to obtain

$$\pi(\theta; p_1) \geq \frac{\sqrt{2\pi}}{e^m} n^{-(m-1)/2} \prod_{j:\theta_j>0} p_{1j}^{-1/2} \geq m^{m/2} e^{-m} \sqrt{2\pi} n^{-(m-1)/2} \geq 0.64 n^{-1.5}$$

where the second inequality uses the AM-GM inequality

$$\prod_{j:\theta_j>0} p_{1j} \leq \left( \frac{1}{m} \sum_j p_j \right)^m = m^{-m}.$$

Therefore,

$$E_\theta[\delta(Y)] \leq \alpha(1 + 3.125 n^{1.5} (1 - \epsilon)^n) \rightarrow \alpha.$$

□

**Proposition 5.1.** (Bayesian updating)

- (1) *Some Bayesians update: there exists a prior  $\pi$  with  $\pi(\Theta_0) \in (0, 1)$  such that  $\pi(\Theta_0 | Y) \neq \pi(\Theta_0)$  with positive  $\pi$ -probability.*
- (2) *There exist (nontrivial) Bayesian priors over  $\theta$  that never update about the probability that monotonicity holds: for any  $c \in (0, 1)$ , there exists a prior distribution  $\pi$  over  $\theta$  such that  $\pi(\theta \in \Theta_0 | Y) = \pi(\theta \in \Theta_0) = c$ ,  $\pi$ -almost surely.*

*Proof.* Let  $\theta_0 \in \Theta_0$  and  $\theta_1 \in \Theta_1$  be two parameter values. By [Proposition 3.1](#),  $f_{\theta_0} \neq f_{\theta_1}$ . Let  $\pi = 0.5\delta_{\theta_0} + 0.5\delta_{\theta_1}$  be such that  $\pi(\Theta_0) = 0.5 \in (0, 1)$ . The posterior probability is such that

$$\pi(\theta_0 | Y = y) = 1 - \pi(\theta_1 | Y = y) = \frac{f_{\theta_0}(y)}{f_{\theta_1}(y) + f_{\theta_0}(y)}.$$



Since  $f_{\theta_0} \neq f_{\theta_1}$  for some  $y$  in the support of one of  $f_{\theta_0}(\cdot)$  and  $f_{\theta_1}(\cdot)$ ,  $\pi(\theta_0 | Y = y) \neq 0.5 = \pi(\theta_0)$  with positive probability. Since  $\theta_0 \in \Theta_0$  is the only point of support under  $\pi$ , which concludes the proof of the first part.

For the second part, by [Lemma A.1](#), there exists priors  $\pi_A$  and  $\pi_B$  such that  $\pi_A(\theta \in \Theta_0) = 1$ ,  $\pi_B(\theta \in \Theta_0) = 0$ , and  $\pi_A(Y = y) = \pi_B(Y = y)$  for all  $y$ . Consider the prior  $\pi_C = c\pi_A + (1 - c)\pi_B$  which mixes with probabilities  $c$  and  $1 - c$  between  $\pi_A$  and  $\pi_B$ . By Bayes' rule, we have that

$$\pi_C(\theta \in \Theta_0 | Y) = \frac{\pi_C(Y | \theta \in \Theta_0) \cdot \pi_C(\theta \in \Theta_0)}{\pi_C(Y)}.$$

However, since  $\pi_A(\theta \in \Theta_0) = 1$  and  $\pi_B(\theta \in \Theta_0) = 0$ , we have that  $\pi_C(Y | \theta \in \Theta_0) = \pi_A(Y)$ . Further  $\pi_C(Y) = c\pi_A(Y) + (1 - c)\pi_B(Y) = \pi_A(Y)$ , where the second equality uses the fact that  $\pi_A(Y) = \pi_B(Y)$ . It follows that  $\pi_C(Y | \theta \in \Theta_0) = \pi_A(Y) = \pi_C(Y)$ . The previous display thus reduces to  $\pi_C(\theta \in \Theta_0 | Y) = \pi_C(\theta \in \Theta_0) = c$ , which gives the second result. □

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