

# Some Characteristics Are Risk Exposures, and the Rest Are Irrelevant\*

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## Abstract

We use a new method to estimate common risk factors and loadings in the cross section of asset returns. The method, Instrumented Principal Components Analysis (IPCA), allows for time-varying loadings in a latent factor return model by introducing observable characteristics that instrument for the unobservable dynamic loadings. If the characteristics' expected return relationship is driven by compensation for exposure to latent risk factors, IPCA will identify the corresponding latent factors. If no such factors exist, IPCA infers that the characteristic effect is compensation without risk and allocates it to an "anomaly" intercept. Studying returns and characteristics at the stock-level, we find that three IPCA factors explain the cross section of average returns significantly more accurately than existing factor models and produce characteristic-associated anomaly intercepts that are small and statistically insignificant. Furthermore, among a large collection of characteristics explored in the literature, only seven are statistically significant in the IPCA specification and are responsible for nearly 100% of the model's accuracy.

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*One of our central themes is that if assets are priced rationally, variables that are related to average returns, such as size and book-to-market equity, must proxy for sensitivity to common (shared and thus undiversifiable) risk factors in returns.*

Fama and French (1993)

*We have a lot of questions to answer: First, which characteristics really provide independent information about average returns? Which are subsumed by others? Second, does each new anomaly variable also correspond to a new factor formed on those same anomalies? ... Third, how many of these new factors are really important?*

Cochrane (2005)

# 1 Introduction

The greatest collective endeavor of the asset pricing field in the past 25 years is the search for an empirical explanation of why different assets earn different average returns. The answer from equilibrium theory is clear—differences in expected returns reflect compensation for different degrees of risk. But the empirical answer has proven more complicated, as some of the largest differences in performance across assets continue to elude a reliable risk-based explanation.

This empirical search centers around return factor models, and arises from the Euler equation for investment returns. With only the assumption of “no arbitrage,” a stochastic discount factor  $m_{t+1}$  exists and, for any excess return  $r_{i,t}$ , satisfies the equation

$$E_t[m_{t+1}r_{i,t+1}] = 0 \quad \Leftrightarrow \quad E_t[r_{i,t+1}] = \underbrace{\frac{\text{Cov}_t(m_{t+1}, r_{i,t+1})}{\text{Var}_t(m_{t+1})}}_{\beta'_{i,t}} \underbrace{\frac{\text{Var}_t(m_{t+1})}{E_t[m_{t+1}]}}_{\lambda_t}. \quad (1)$$

The loadings,  $\beta_{i,t}$ , are interpretable as exposures to systematic risk factors, and  $\lambda_t$  as the risk prices associated with those factors. More specifically, when  $m_{t+1}$  is linear in factors  $f_{t+1}$ , this maps to a factor model for excess returns of the form<sup>1</sup>

$$r_{i,t+1} = \alpha_{i,t} + \beta'_{i,t}f_{t+1} + \epsilon_{i,t+1} \quad (2)$$

where  $E_t(\epsilon_{i,t+1}) = E_t[\epsilon_{i,t+1}f_{t+1}] = 0$ ,  $E_t[f_{t+1}] = \lambda_t$ , and, perhaps most importantly,  $\alpha_{i,t} = 0$  for all  $i$  and  $t$ . The factor framework in (2) that follows from the asset pricing Euler equation

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<sup>1</sup>Ross (1976), Hansen and Richard (1987).

(1) is the setting for most empirical analysis of expected returns across assets.

There are many obstacles to empirically analyzing equations (1) and (2), the most important being that the factors and loadings are unobservable.<sup>2</sup> There are two common approaches that researchers take.

The first is to pre-specify factors based on previously established knowledge about the empirical behavior of average returns, treat these factors as fully observable by the econometrician, and then estimate betas and alphas via regression. This approach is exemplified by Fama and French (1993). A shortcoming of this approach is that it requires previous understanding of the cross section of average returns. But this is likely to be a partial understanding at best, and at worst is exactly the object of empirical interest.<sup>3</sup>

The second approach is to treat risk factors as latent and use factor analytic techniques, such as PCA, to simultaneously estimate the factors and betas from the panel of realized returns, a tactic pioneered by Chamberlain and Rothschild (1983) and Connor and Korajczyk (1988). This method uses a purely statistical criterion to derive factors, and has the advantage of requiring no ex ante knowledge of the structure of average returns. A shortcoming of this approach is that PCA is ill-suited for estimating conditional versions of equation (2) because it can only accommodate static loadings. Furthermore, PCA lacks the flexibility for a researcher to incorporate other data beyond returns to help identify a successful asset pricing model.

## 1.1 Our Methodology

In this paper, we use a new method called instrumental principal components analysis, or IPCA, that estimates market risk factors and loadings by exploiting beneficial aspects of both approaches while bypassing their shortcomings. IPCA allows factor loadings to partially depend on observable asset characteristics that serve as instrumental variables for the latent dynamic loadings. IPCA consistently estimates the mapping between the characteristics and loadings. It provides a formal statistical link between characteristics and expected

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<sup>2</sup>Even in theoretical models with well-defined risk factors, such as the CAPM, the theoretical factor of interest is generally unobservable and must be approximated, as discussed by Roll (1977).

<sup>3</sup>Fama and French (1993) note that “Although size and book-to-market equity seem like ad hoc variables for explaining average stock returns, we have reason to expect that they proxy for common risk factors in returns. ... We think there is appeal in the simple way we define mimicking returns for the stock-market and bond-market factors. But the choice of factors, especially the size and book-to-market factors, is motivated by empirical experience. Without a theory that specifies the exact form of the state variables or common factors in returns, the choice of any particular version of the factors is somewhat arbitrary.”

returns that is consistent with the equilibrium asset pricing principle that risk premia are solely determined by risk exposures. And, because instruments help consistently recover the loadings, IPCA is then also able to consistently estimate the latent factors associated with these loadings. In this way, IPCA allows the factor model to incorporate the robust empirical fact that stock characteristics provide reliable conditioning information for expected returns. By including instruments, the researcher can leverage previous, but imperfect, knowledge about the structure of average returns in order to improve their estimates of factors and loadings, without the unrealistic requirement that the researcher can correctly specify the exact factors *a priori*.

Our central motivation in developing IPCA is to build a model and estimator that admits the possibility that characteristics line up with average returns because they proxy for loadings on common risk factors. Indeed, if the “characteristics/expected return” relationship is driven by compensation for exposure to latent risk factors, IPCA will identify the corresponding latent factors and betas. But, if no such factors exist, the characteristic effect will be absorbed in an intercept. This immediately leads to an intuitive intercept test that discriminates whether a characteristic-based return phenomenon is consistent with a beta/expected return model, or if it is compensation without risk (a so-called “anomaly”). This test generalizes alpha-based tests such as Gibbons, Ross, and Shanken (1989, GRS). Rather than asking the GRS question “do some pre-specified factors explain the anomaly?,” our IPCA test asks “Does there *exist* some set of common latent risk factors that explain the anomaly?” It also provides tests for the importance of particular groups of instruments while controlling for all others, analogous to regression-based  $t$  and  $F$  tests, and thus offers a means to address questions raised in the Cochrane (2005) quote above.

A standard protocol has emerged in the literature: When researchers propose a new characteristic that aligns with future asset returns, they build a portfolio or set of portfolios that exploit the characteristic’s predictive power and test the alphas of these portfolios relative to some previously established pricing factors (such as those from Fama and French, 1993, 2015). This protocol is unsatisfactory as it fails to fully account for the gamut of proposed characteristics in prior literature. Our method offers a different protocol that treats the multivariate nature of the problem. When a new anomaly characteristic is proposed, it can be included in an IPCA specification that also includes the long list of characteristics from past studies. Then, IPCA can estimate the proposed characteristic’s marginal contribution to the model’s factor loadings or, if need be, its anomaly intercepts, after controlling for other characteristics in a complete multivariate analysis.

## 1.2 Findings

Our analysis judges asset pricing models on two criteria. First, a successful factor model should excel in describing the common variation in realized returns. That is, it should accurately describe systematic risks. We measure this according to a factor model’s total panel  $R^2$ . We define total  $R^2$  as the fraction of variance in  $r_{i,t}$  described by  $\hat{\beta}'_{i,t-1}\hat{f}_t$ , where  $\hat{\beta}_{i,t-1}$  are estimated dynamic loadings and  $\hat{f}_t$  are the model’s estimated or pre-specified common risk factors. The total  $R^2$  thus includes the explained variation due to contemporaneous factor realizations and dynamic factor exposures, aggregated over all assets and time periods.

Second, a successful asset pricing model should describe differences in average returns across assets. That is, it should accurately describe risk compensation. To assess this, we define a model’s predictive  $R^2$  as the explained variation in  $r_{i,t}$  due to  $\hat{\beta}'_{i,t-1}\hat{\lambda}$ , the conditional expected return on asset  $i$  at based on information at time  $t - 1$ , where  $\hat{\lambda}$  is the vector of estimated factor risk prices.<sup>4</sup>

Our empirical analysis uses data on returns and characteristics for over 12,000 stocks from 1962–2014. Our preferred IPCA specification includes three factors and restricts all stock-level intercepts to be zero, and in this case IPCA achieves a total  $R^2$  for returns of 17.8%. With five factors the total  $R^2$  rises to 19.3%—as a benchmark, the matched sample total  $R^2$  from the Fama-French five-factor model is 21.9%. Thus, IPCA is a competitive model for describing the variability and hence riskiness of stock returns.

Perhaps more importantly, the factor loadings estimated from IPCA provide an excellent description of conditional expected stock returns. In the three-factor IPCA model, the estimated compensation for factor exposures ( $\hat{\beta}'_{i,t}\hat{\lambda}$ ) delivers a predictive  $R^2$  for returns of 1.4%. In the matched sample, the predictive  $R^2$  from the Fama-French five-factor model is 0.3%. Thus, IPCA is a superior model for describing risk compensation.

If we instead use standard PCA to estimate the latent three-factor specification, it delivers a 26.2% total  $R^2$ . However, PCA produces a *negative* predictive  $R^2$ , showing that it provides no explanatory power for differences in average returns across stocks. PCA is the linear latent factor model that maximizes the total  $R^2$  statistic by construction. IPCA places additional restrictions on the latent factor specification that make it weakly inferior to PCA in terms of in-sample total  $R^2$ . However, by introducing additional structure on the latent factor specification, IPCA improves the model’s performance in isolating compensated risk exposures

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<sup>4</sup>We discuss our definition of predictive  $R^2$  in terms of the unconditional risk price estimate,  $\hat{\lambda}$ , rather than a conditional risk price estimate, in Section 5.

while still maintaining large explanatory power for realized return covariation. In summary, IPCA is the most successful model we analyze for jointly explaining realized variation in returns (i.e., systematic risks) and differences in average returns (i.e., risk compensation).

The above model performance statistics are based on in-sample estimation. If we instead use recursive out-of-sample estimation to calculate predictive  $R^2$ 's for stock returns, we find that IPCA continues to outperform alternatives. The three-factor IPCA predictive  $R^2$  is 0.5% per month out-of-sample, versus 0.2% for the Fama-French five-factor model and again a negative predictive  $R^2$  from PCA.

Furthermore, by linking factor loadings to observable data, IPCA tremendously reduces the dimension of the parameter space compared to models with observable factors and even compared to standard PCA. To accommodate the more than 12,000 stocks in our sample, the Fama-French five-factor model estimates 57,260 loading parameters. Three-factor PCA estimates 40,236 parameters including the time series of latent factors. Three-factor IPCA estimates only 2,013 (including each realization of the latent factors), or 95% fewer parameters than the pre-specified factor model or PCA, and incorporates dynamic loadings without relying on ad hoc rolling estimation approaches. It does this by essentially redefining the identity of a stock in terms of its characteristics, rather than in terms of the stock identifier. Thus, once a stock's characteristics are known, only a small number of parameters (which are common to all assets) are required to map the observed characteristic values into betas.

In the aforementioned results, IPCA's success in explaining differences in average returns across stocks comes solely through its description of factor loadings—it restricts intercept coefficients to zero for all stocks. The question remains as to whether there are differences in average returns across stocks that align with characteristics and that are unexplained by exposures to IPCA factors.

By allowing intercepts to also depend on characteristics, IPCA provides a test for whether characteristics help explain expected returns above and beyond their role in factor loadings. Including alphas in the IPCA model generally improves its ability to explain average returns. When there are very few factors in the model ( $K = 0, 1$ , or  $2$ ), we can reject the null hypothesis of zero intercepts. Evidently, with three or fewer factors, the specification of factor exposures is not rich enough to assimilate all of the return predictive content in stock characteristics. Thus, the excess predictability from characteristics spills into the intercept to an economically large and statistically significant extent.

However, when we consider specifications with  $K \geq 3$ , the improvement in model fit due to non-zero intercepts becomes small and statistically insignificant. The economic conclusion

is that a three-dimensional risk structure coincides with information in stock characteristics in such a way that i) risk exposures are exceedingly well described by stock characteristics, and ii) the residual return predicability from characteristics, above and beyond that in factor loadings, falls to effectively zero, obviating the need to resort to “anomaly” intercepts.

The dual implication of IPCA’s superior explanatory power for average stock returns is that IPCA factors are closer to being multivariate mean-variance efficient than factors in competing models. We show that the tangency portfolio of factors from the three-factor IPCA specification achieves an *ex ante* (i.e., out-of-sample) Sharpe ratio of 1.3, and with five factors rises to 1.8, versus 0.9 for the five Fama-French factors.

Lastly, IPCA offers a test for which characteristics are significantly associated with factor loadings (and thus expected returns) while controlling for all other characteristics, in analogy to *t*-tests of independent variables in a regression model. In our main specification, we find that nine of the 36 firm characteristics in our sample are statistically significant at the 5% significance level, with seven of these significant at the 1% level. These include essentially two types of variables: valuation ratios (e.g., book-to-market, earnings-to-price) and recent stock return performance (e.g., short-term reversal and price relative to trailing 52-week high). If we re-estimate the model using the subset of seven highly-significant regressors, we find that model fit is nearly identical to the full 36-characteristic specification. The fact that only a small subset of characteristics is necessary to explain variation in realized and expected stock returns shows that most characteristics are statistically irrelevant for understanding the cross section of returns once they are evaluated in an appropriate multivariate context. Furthermore, that we cannot reject the null of zero alphas using only three IPCA risk factors leads us to conclude that those few characteristics that are significant enter the model because they help explain assets’ exposures to systematic risks, and do not appear to represent anomalous compensation without risk.

### 1.3 Literature

Our work builds on several literatures studying the behavior of stock returns. Calling this literature large is a gross understatement. Rather than attempting a thorough review, we briefly describe three primary strands of literature most closely related to our analysis and highlight a few exemplary contributions in each.

One branch of this literature analyzes latent factor models for returns, beginning with Ross’s (1976) seminal APT. Empirical contributions to this literature rely on principal component

estimation, such as Chamberlain and Rothschild (1983) and Connor and Korajczyk (1988, 1989, 1991). Our primary innovation relative to this literature is to bring new information beyond returns themselves into model estimation and, in doing so, improve the efficiency of estimation and make it possible to tractably estimate factor models with dynamic loadings.

Another strand of literature models factor loadings as functions of observables. Most closely related are models in which factor exposures are functions of firm characteristics, dating at least to Rosenberg (1974). In contrast to our contributions, that analysis is primarily theoretical, assumes that factors are observable, and does not provide a testing framework. Ferson and Harvey (1991) allow for dynamic betas as asset-specific functions of macroeconomic variables. They differ from our analysis by relying on observable factors and focusing on macro rather than firm-specific instrumental variables. Daniel and Titman (1996) directly compare stock characteristics to factor loadings in their ability to explain differences in average returns, an approach recently extended by Chordia, Goyal, and Shanken (2015). IPCA is unique in nesting competing characteristic and beta models of returns while simultaneously estimating the latent factors that most accurately coincide with characteristics as loadings, rather than relying on pre-specified factors.

A third literature models stock returns as a joint function of many characteristics. This literature has emerged only recently in response to the accumulation of a large body of research on predictive stock characteristics and exploits more recently developed statistical techniques for high-dimensional predictive models. Lewellen (2015) analyzes the joint predictive power of up to 15 characteristics in OLS regression. Light, Maslov, and Rytchkov (2016) and Freyberger, Neuhierl, and Weber (2017) consider much larger collections of predictors and address concomitant statistical challenges using partial least squares and LASSO, respectively. These papers take a pure return forecasting approach and do not consider characteristics as loadings or conduct asset pricing tests. In this strand of literature, the most closely related papers to ours are Kozak, Nagel, and Santosh (forthcoming, 2017). Kozak et. al (forthcoming) show that a small number of principal components from 15 anomaly portfolios (from Novy-Marx and Velikov, 2015) are able to price those same portfolios with insignificant alphas. Kozak et. al (2017) consider a latent SDF and use shrinkage to isolate a subset of characteristic portfolios with good out-of-sample explanatory power for average returns. Our approach and findings differ in a few ways. First, our IPCA method selects pricing factors based on a factor variance criterion, then subsequently and separately tests whether loadings on these factors explain differences in average returns.<sup>5</sup> Second, our ap-

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<sup>5</sup>Kozak et. al (2017) directly model risk prices as functions of average portfolio returns, which amounts to a mechanical in-sample association between their estimated SDF and average returns in their portfolio data. They use shrinkage to identify a model with reliable, non-mechanical out-of-sample explanatory power



proach derives formal tests and emphasizes statistical model comparison in a frequentist setting. Our tests i) differentiate whether a characteristic is better interpreted as a proxy for systematic risk exposure or as an anomaly alpha, ii) assess the incremental explanatory power of an individual characteristic against a (potentially high dimension) set of competing characteristics, and iii) compares latent factors against pre-specified alternative factors. The results of these tests conclude that stock characteristics are best interpreted as risk loadings, that most of the characteristics proposed in the literature contain no incremental explanatory power for returns, and that commonly studied pre-specified factors are inefficient in a mean-variance sense.

We describe the IPCA model in Section 2 and describe the estimator in Section 3. Section 4 develops asset pricing and model comparison tests in the IPCA setting. Section 5 reports our empirical findings and Section 6 concludes.

## 2 Model

The general IPCA model specification for an excess return  $r_{i,t+1}$  is

$$r_{i,t+1} = \alpha_{i,t} + \beta_{i,t}f_{t+1} + \epsilon_{i,t+1}, \quad (3)$$

$$\alpha_{i,t} = z'_{i,t}\Gamma_{\alpha} + \nu_{\alpha,i,t}, \quad \beta_{i,t} = z'_{i,t}\Gamma_{\beta} + \nu_{\beta,i,t}.$$

The system is comprised of  $N$  assets over  $T$  periods. The model allows for dynamic factor loadings,  $\beta_{i,t}$ , on a  $K$ -vector of latent factors,  $f_{t+1}$ . Loadings potentially depend on observable asset characteristics contained in the  $L \times 1$  instrument vector  $z_{i,t}$ .

The specification of  $\beta_{i,t}$  is central to our analysis and plays two roles. First, instrumenting the estimation of latent factor loadings with observable characteristics allows additional data to shape the factor model for returns. This differs from traditional latent factor techniques like PCA that estimate the factor structure solely from returns data. Anchoring the loadings to observable instruments can make the estimation more efficient and thereby improve model performance. This is true even if the instruments and true loadings are constant over time (see Fan, Liao, and Wang 2016). Second, incorporating time-varying instruments makes it possible to estimate dynamic factor loadings, which is valuable when one seeks a model of conditional return behavior.

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for returns.

The matrix  $\Gamma_\beta$  defines the mapping between a potentially large number of characteristics and a small number of risk factor exposures. Estimation of  $\Gamma_\beta$  amounts to finding linear combinations of candidate characteristics that best describe the latent factor loading structure.<sup>6</sup> Our model emphasizes dimension reduction of the characteristic space. If there are many characteristics that provide noisy but informative signals about a stock’s risk exposures, then aggregating characteristics into linear combinations isolates the signal and averages out the noise. Any behavior of dynamic loadings that is orthogonal to the instruments falls into  $\nu_{\beta,i,t}$ . With this term, the model recognizes that firms’ risk exposures are not perfectly recoverable from observable firm characteristics.

The  $\Gamma_\beta$  matrix also allows us to confront the challenge of migrating assets. Stocks evolve over time, moving for example from small to large, growth to value, high to low investment intensity, and so forth. Received wisdom in the asset pricing literature is that stock expected returns evolve along with these characteristics. But the very fact that the “identity” of the stock changes over time makes it difficult to model stock-level conditional expected returns using simple time series methods. The standard response to this problem is to dynamically form portfolios that hold average characteristic values within the portfolio approximately constant. But if an adequate description of an asset’s identity requires several characteristics, this portfolio approach becomes infeasible due to the proliferation of portfolios. IPCA provides a natural and general solution: Parameterize betas as a function of the characteristics that determine a stock’s expected return. In doing so, migration in the asset’s identity is tracked through its betas, which are themselves defined by their characteristics in a way that is consistent among all stocks ( $\Gamma_\beta$  is a global mapping shared by all stocks). Thus, IPCA avoids the need for a researcher to perform the *a priori* dimension reduction that gathers test assets into portfolios. Instead, the model accommodates a high-dimensional system of assets (individual stocks) by estimating a dimension reduction that represents the identity of a stock in terms of its characteristics.

Our analysis considers a null hypothesis in which characteristics do *not* proxy for alpha:  $\Gamma_\alpha$  is restricted to zero. The unrestricted IPCA specification in (3) includes an alternative hypothesis that conditional expected returns have non-zero intercepts that depend on stock characteristics. The structure of  $\alpha_{i,t}$  is a linear combination of instruments and may have an unobservable component  $\nu_{\alpha,i,t}$ , mirroring the specification of  $\beta_{i,t}$ . IPCA estimates  $\alpha_{i,t}$

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<sup>6</sup>The model imposes that  $\beta_{i,t}$  is linear in instruments. Yet it accommodates non-linear associations between characteristics and exposures by allowing instruments to be non-linear transformations of raw characteristics. For example, one might consider including the first, second, and third power of a characteristic into the instrument vector to capture nonlinearity via a third-order Taylor expansion, or interactions between characteristics. Relatedly,  $z_{i,t}$  can include time-invariant instruments.

by finding the linear combination of characteristics (with weights given by  $\Gamma_\alpha$ ) that best describes conditional expected returns *after* controlling for the role of characteristics in systematic risk exposure. If characteristics align with average stock returns *differently* than they align with risk factor loadings, then IPCA will estimate a non-zero  $\Gamma_\alpha$ , conceding anomalous compensation for holding stocks in excess of that warranted by systematic risk exposure.

We focus on models in which the number of factors,  $K$ , is small, imposing a view that the empirical content of an asset pricing factor model is parsimony describing sources of systematic risk. At the same time, we consider the number of instruments,  $L$ , to be potentially large, as literally hundreds of characteristics have been put forward by the literature to explain average stock returns. And, because any individual characteristic is likely to be a noisy representation of true factor exposures, accommodating large  $L$  allows the model to average over characteristics in a way that reduces noise and more accurately reveals true exposures.

### 3 Estimation

In this section we provide a conceptual overview of IPCA estimation. Our description here introduces two identifying assumptions and discusses their role in estimation. Kelly, Pruitt, and Su (2017) derive the IPCA estimator and prove that, together with the identifying assumptions, IPCA consistently estimates model parameters and latent factors as the number of assets and the time dimension simultaneously grow large, as long as factors and residuals satisfy weak regularity conditions (their Assumptions 2 and 3). We refer interested readers to that paper for technical details.

#### 3.1 Restricted Model ( $\Gamma_\alpha = \mathbf{0}$ )

We first describe estimation of the restricted model in which anomaly alphas are fixed at zero. In particular, it imposes  $\Gamma_\alpha = \mathbf{0}_{L \times 1}$ , ruling out the possibility that characteristics capture “anomalous” compensation without risk. Instead, it maintains that characteristics explain expected returns only insofar as they proxy for systematic risk exposures. In this case, equation (3) becomes

$$r_{i,t+1} = z'_{i,t} \Gamma_\beta f_{t+1} + \epsilon^*_{i,t+1} \quad (4)$$

where  $\epsilon^*_{i,t+1} = \epsilon_{i,t+1} + \nu_{\alpha,i,t} + \nu_{\beta,i,t} f_{t+1}$ . That is, our data generating process has two sources of noise that affect estimation of factors and loadings. The first comes from the fact that

characteristics do not perfectly reveal the true factor model parameters (reflected in  $\nu_{\alpha,i,t}$  and  $\nu_{\beta,i,t}$ ) and the second from returns being determined in part by idiosyncratic firm-level shocks ( $\epsilon_{i,t+1}$ ).

We derive the estimator using the vector form of equation (4),

$$r_{t+1} = Z_t \Gamma_\beta f_{t+1} + \epsilon_{t+1}^*,$$

where  $r_{t+1}$  is an  $N \times 1$  vector of individual firm returns,  $Z_t$  is the  $N \times L$  matrix that stacks the characteristics of each firm, and  $\epsilon_{t+1}^*$  likewise stacks individual firm residuals. Our estimation objective is to minimize the sum of squared composite model errors:

$$\min_{\Gamma_\beta, F} \sum_{t=1}^{T-1} (r_{t+1} - Z_t \Gamma_\beta f_{t+1})' (r_{t+1} - Z_t \Gamma_\beta f_{t+1}). \quad (5)$$

The value of  $f_{t+1}$  that minimizes (5) satisfies the first-order condition

$$\hat{f}_{t+1} = (\Gamma_\beta' Z_t' Z_t \Gamma_\beta)^{-1} \Gamma_\beta' Z_t' r_{t+1}. \quad (6)$$

In a static latent factor model of returns with  $r_t = \beta f_t + \epsilon_t$  (e.g., Connor and Korajczyk, 1988), the PCA factor solution is  $\hat{f}_{t+1} = (\beta' \beta)^{-1} \beta' r_{t+1}$ . Equation (6) is the analogous IPCA solution in the presence of dynamic instrumented betas.

Substituting the  $f_{t+1}$  solution into the original objective yields a concentrated objective function for  $\Gamma_\beta$ :

$$\max_{\Gamma_\beta} \text{tr} \left( \sum_{t=1}^{T-1} (\Gamma_\beta' Z_t' Z_t \Gamma_\beta)^{-1} \Gamma_\beta' Z_t' r_{t+1} r_{t+1}' Z_t \Gamma_\beta \right). \quad (7)$$

It is helpful to contrast this concentrated objective with the concentrated objective for the static model, which takes the form

$$\max_{\beta} \text{tr} \left( \sum_t (\beta' \beta)^{-1} \beta' r_{t+1} r_{t+1}' \beta \right).$$

The static objective maximizes a sum of Rayleigh quotients that all have the same denominator,  $\beta' \beta$ . The well-known PCA solution for  $\beta$  in this setting is the first  $K$  eigenvectors of  $\sum_t r_{t+1} r_{t+1}'$ .

The concentrated IPCA objective is more challenging because the Rayleigh quotient denominators,  $\Gamma_\beta' Z_t' Z_t \Gamma_\beta$ , are different for each element of the sum. Because of this complication,

there is not generally an eigenvector solution for  $\Gamma_\beta$  analogous to PCA's solution for  $\beta$ . Unless more structure is placed on the problem, the  $\Gamma_\beta$  solution must be found numerically.

While possible in principle, numerical optimization of this objective becomes extremely costly for moderately high-dimensional systems. The great advantage of PCA is that leading eigenvectors of a matrix are easy to compute even in very high dimensions.

With the following assumption, it is possible to solve the IPCA problem for  $\Gamma_\beta$  analytically using an eigenvector decomposition rather than numerical optimization.

**Assumption 1.** The matrix of instruments is orthonormal:  $Z_t'Z_t = \mathbb{I}_L \forall t$ .

When instruments are orthonormal period-by-period,<sup>7</sup> the objective in (7) reduces to

$$\max_{\Gamma_\beta} \text{tr} \left( \sum_{t=1}^{T-1} (\Gamma_\beta' \Gamma_\beta)^{-1} \Gamma_\beta' Z_t' r_{t+1} r_{t+1}' Z_t \Gamma_\beta \right). \quad (8)$$

That is, the objective function collapses to a sum of homogeneous Rayleigh quotients. As a result, the  $K$  leading eigenvectors of  $\sum_t Z_t' r_{t+1} r_{t+1}' Z_t$  satisfy the maximization problem and thus estimate  $\Gamma_\beta$ .

More specifically, we derive the algebraic solution for  $\Gamma_\beta$  via the following eigenvalue decomposition:

$$USU' = \sum_t Z_t' r_{t+1} r_{t+1}' Z_t,$$

The IPCA estimator of  $\Gamma_\beta$  is

$$\hat{\Gamma}_\beta = U_K \quad (9)$$

where the columns of  $U$  are arranged in decreasing eigenvalue order and  $U_K$  denotes the first  $K$  columns of  $U$ . The factor estimates are

$$\hat{f}_{t+1} = \hat{\Gamma}_\beta' (Z_t' r_{t+1}). \quad (10)$$

The unconditional risk prices for each factor, defined as  $\lambda = E[f_t]$ , are thus estimated as

$$\hat{\lambda} = T^{-1} \sum_t \hat{f}_t. \quad (11)$$

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<sup>7</sup>We can directly impose this assumption on the data. In particular, given some matrix of “raw” instruments  $\tilde{Z}_t$ , we construct orthonormal instruments  $Z_t$  using the Gram-Schmidt process as described in Section 5.

As in any latent factor model,  $\Gamma_\beta$  and  $f_{t+1}$  are unidentified in the sense that any set of solutions can be rotated into another solution  $\Gamma_\beta R^{-1}$  and  $Rf_{t+1}$  for a non-singular  $K$ -dimensional rotation matrix  $R$ . The standard PCA problem deals with this by making the identification assumption that  $\beta'\beta = \mathbb{I}_K$ . The following identification assumption for IPCA resolves this rotational indeterminacy.

**Assumption 2.** The mapping from instruments to betas is orthonormal:  $\Gamma'_\beta \Gamma_\beta = \mathbb{I}_K$ .

Choosing  $\Gamma_\beta$  to itself be orthonormal pins down a unique rotation of the model parameters and factors. Under Assumptions 1 and 2, the inner product of observable components in dynamic betas (that is,  $Z_t \Gamma_\beta$ ) is the identity matrix. Thus, our assumption can be viewed as the dynamic model counterpart to the standard PCA identification assumption for static models (see, for example, Assumption F1(a) in Stock and Watson, 2002a).

### 3.1.1 A Managed Portfolio Interpretation of IPCA

The PCA estimator of a static return factor model studied by Connor and Korajczyk (1988) applies the singular value decomposition to the panel of individual asset excess returns  $r_{i,t}$ . Our derivation shows that the IPCA problem is solved by applying the singular value decomposition not to raw returns, but to returns interacted with instruments. Consider the  $L \times 1$  vector defined as

$$x_{t+1} = Z'_t r_{t+1}. \quad (12)$$

This is the time  $t+1$  realization of returns on a set of  $L$  managed portfolios. The  $l^{th}$  element of  $x_{t+1}$  is a weighted average of stock returns with weights determined by the value of  $l^{th}$  characteristic for each stock at time  $t$ .

Stacking time series observations produces the  $T \times L$  matrix  $X = [x'_1, \dots, x'_T]'$ . Each column of  $X$  is a time series of returns on a characteristic-managed portfolio. If the first three characteristics are, say, size, value, and momentum, then the first three columns of  $X$  are time series of returns to portfolios managed on the basis of stocks' size, value, and momentum characteristics.

As one uses more and more characteristics to instrument for latent factor exposures, the number of characteristic-managed portfolios in  $X$  grows. Prior empirical work shows that there tends to be a high degree of common variation in anomaly portfolios (e.g. Novy-Marx and Velikov, 2015; Kozak, Nagel, and Santosh, forthcoming). IPCA recognizes this and estimates factors and loadings by focusing on the common variation in  $X$ . It estimates factors as the  $K$  linear combinations of  $X$ 's columns, or "portfolios of portfolios," that

best explain covariation among the panel of managed portfolios. It does so by choosing loadings and factors associated with the  $K$  leading eigenvalues of the second moment matrix of managed portfolios,  $X'X = \sum_t Z_t' r_{t+1} r_{t+1}' Z_t$ .

IPCA can also be viewed as a generalization of period-by-period cross section regressions as employed in Fama and MacBeth (1973). Each portfolio realization  $x_{t+1}$  is the vector of coefficients in the multiple regression of  $r_{t+1}$  on  $Z_t$  (because  $Z_t' Z_t = \mathbb{I}_L$ ). When  $K = L$  there is no dimension reduction—the estimates of  $f_{t+1}$  are the characteristic-managed portfolios themselves and are equal to the period-wise Fama-MacBeth regression coefficients. But when  $K < L$ , IPCA's  $f_{t+1}$  estimate is a *constrained* Fama-MacBeth regression coefficient. The constrained regression not only estimates return loadings on lagged characteristics, but it must also choose a reduced-rank set of regressors—the  $K < L$  combinations of characteristics that best fit the cross section regression.

Instead of representing IPCA in the space of excess stock returns, we can equivalently represent it in the space of characteristic-managed portfolio returns:

$$x_{t+1} = \Gamma_\beta f_{t+1} + d_{t+1}. \quad (13)$$

Equation (13) follows from multiplying (4) by  $Z_t'$  and defining  $d_{t+1} = Z_t' \epsilon_{t+1}^*$ . It provides a different interpretation of model parameters through the lens of portfolios. First we see that, for appropriately oriented portfolios,  $\Gamma_\beta$  can be viewed as a set of static portfolio loadings on the latent pricing factors. Next, factor estimates from equation (10) can be re-defined as a cross section regression of  $x_t$  on the estimated loadings,

$$\hat{f}_t = \left( \hat{\Gamma}_\beta' \hat{\Gamma}_\beta \right)^{-1} \hat{\Gamma}_\beta' x_t. \quad (14)$$

And, denoting the time series average of  $x_t$  as the  $L \times 1$  vector  $\bar{x}$ , equation (11) can be equivalently stated as

$$\hat{\lambda} = \left( \hat{\Gamma}_\beta' \hat{\Gamma}_\beta \right)^{-1} \hat{\Gamma}_\beta' \bar{x}. \quad (15)$$

That is, risk prices are equal to the cross section regression coefficient of average managed portfolio returns on their IPCA factor exposures, paralleling the risk price estimator of Fama and MacBeth (1973).

A common dilemma facing empirical asset pricing tests is how to choose appropriate test assets. In the asset pricing tests that follow, IPCA overcomes this dilemma through an equivalence between two choices of test assets. On one hand, IPCA tests can be viewed as using the set of test assets with the finest possible resolution—the set of individual stocks.

On the other hand, IPCA’s tests can be viewed as using characteristic-managed portfolios,  $x_t$ , as the set of test assets, which have comparatively low dimension and average out a substantial degree of idiosyncratic stock risk. The asset pricing literature has struggled with the question of which test assets are most appropriate for evaluating models (Lewellen, Nagel, and Shanken, 2010; Daniel and Titman, 2012). Our model and the IPCA estimator dictate a specific set of characteristic-managed portfolios to be used as test assets—those comprising  $X$ —while explicitly mapping the test assets to individual stocks.<sup>8</sup>

### 3.2 Unrestricted Model ( $\Gamma_\alpha \neq 0$ )

The unrestricted IPCA model allows for intercepts that are functions of the instruments, thereby admitting the possibility of “anomalies” in which expected returns depend on characteristics in a way that is not explained by exposure to systematic risk. Like the factor specification in (4), the unrestricted IPCA model assumes that intercepts are a linear combination of instruments with weights defined by the  $L \times 1$  parameter vector  $\Gamma_\alpha$ :

$$r_{i,t+1} = z'_{i,t}\Gamma_\alpha + z'_{i,t}\Gamma_\beta f_{t+1} + \epsilon_{i,t+1}^*. \quad (16)$$

To estimate model (16), we set  $\hat{\Gamma}_\beta$  equal to the solution of equation (9), thus holding the estimate of  $\Gamma_\beta$  fixed between the restricted and unrestricted models. In the unrestricted model, managed portfolios are represented as  $x_{t+1} = \Gamma_\alpha + \Gamma_\beta f_{t+1} + d_{t+1}$ , in analogy with representation (13) for the unrestricted model. It is immediate, then, that  $\hat{\Gamma}_\alpha$  is estimated as the time series average of portfolio residuals ( $d_t$ ) from the restricted model. Or, from equation (15),  $\hat{\Gamma}_\alpha$  is equivalently defined as the residuals from a regression of average characteristic-sorted returns,  $\bar{x}$ , onto  $\Gamma_\beta$ . That is, the anomaly intercepts in unrestricted IPCA are the portfolio pricing errors that remain after controlling for systematic risk exposures.

## 4 Asset Pricing Tests

In this section we develop three hypothesis tests that are central to our empirical analysis. The first is designed to test the zero alpha condition that distinguishes the restricted and unrestricted IPCA models of Sections 3.1 and 3.2. The second tests whether a given IPCA

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<sup>8</sup>A further convenience of the managed portfolio representation is that avoids issues with missing observations in stock-level data. In particular, when constructing managed portfolios in equation (12), we evaluate this inner product as a sum over elements of  $Z_t$  and  $r_{t+1}$  for which both terms in the cross-product are non-missing. Thus (12) is a slight abuse of notation.



specification significantly improves over an observable factor model (such as the Fama-French five-factor model) in describing a panel of asset returns. The third tests the incremental significance of an individual characteristic or set of characteristics while simultaneously controlling for all other characteristics.

#### 4.1 Testing $\Gamma_\alpha = \mathbf{0}_{L \times 1}$

When a characteristic lines up with expected returns in the cross section, the unrestricted IPCA estimator in Section 3.2 decides how to split that association. Does the characteristic proxy for exposure to common risk factors? If so, IPCA will attribute the characteristic to beta via  $\hat{\beta}_{i,t} = z'_{i,t} \hat{\Gamma}_\beta$ , thus interpreting the characteristic/expected return relationship as compensation for bearing systemic risk. Or, does the characteristic capture anomalous differences in average returns that are unassociated with systematic risk? In this case, IPCA will be unable to find common factors for which characteristics serve as loadings, so it will attribute the characteristic to alpha via  $\hat{\alpha}_{i,t} = z'_{i,t} \hat{\Gamma}_\alpha$ . In the unrestricted model, any cross-sectional correlation between expected returns and a characteristic is exhaustively attributed to the characteristic through either one or both of these avenues.

In the restricted model, the association between characteristics and alphas is disallowed. If the data truly call for an anomaly alpha, then the restricted model is misspecified and will produce a poor fit compared to the unrestricted model that allows for alpha. The distance between unrestricted alpha estimates and zero summarizes the improvement in model fit from loosening the alpha restriction. If this distance is statistically large (i.e., relative to sampling variation), we can conclude that the true alphas are non-zero.

We propose a test of the zero alpha restriction that formalizes this logic. We are interested in testing the null hypothesis

$$H_0 : \Gamma_\alpha = \mathbf{0}_{L \times 1}$$

against the alternative hypothesis

$$H_1 : \Gamma_\alpha \neq \mathbf{0}_{L \times 1}.$$

In the IPCA model, characteristics determine alphas only if  $\Gamma_\alpha$  is non-zero. The null therefore states that alphas are unassociated with characteristics in the instrument vector  $z_{i,t}$ . Because the hypothesis is formulated in terms of the common parameter, this is a joint statement for all assets in the system.

Note that  $\Gamma_\alpha = \mathbf{0}_{L \times 1}$  does not rule out the existence of alphas entirely. From the model definition in equation (3), we see that  $\alpha_{i,t}$  may differ from zero because  $\nu_{\alpha,i,t}$  is non-zero. That is, the null allows for some mispricing, as long as mispricings are truly idiosyncratic and unassociated with characteristics in the instrument vector. Likewise, the alternative hypothesis is not concerned with alphas arising from the idiosyncratic  $\nu_{\alpha,i,t}$  mispricings. Instead, it focuses on the more economically interesting mispricings that may arise as a regular function of observable characteristics.

In statistical terms,  $\Gamma_\alpha \neq \mathbf{0}_{L \times 1}$  is a constrained alternative. This contrasts, for example, with the Gibbons, Ross, and Shanken (1989, GRS henceforth) test that studies the unconstrained alternative  $\alpha_i = 0 \forall i$ . In GRS, each  $\alpha_i$  is estimated as an intercept in a time series regression. GRS alphas are therefore residuals, not a model. Our constrained alternative is itself a model that links stock characteristics to anomaly expected returns via a fixed mapping that is common to all firms. If we reject the null IPCA model, we do so in favor of a specific model for how alphas relate to characteristics. In this sense our asset pricing test is a frequentist counterpart to Barillas and Shanken's (forthcoming) Bayesian argument that it should take a model to beat a model. This has the pedagogical advantage that, if we statistically reject that  $H_0$  in favor of  $H_1$ , we can further determine which elements of  $\Gamma_\alpha$  (and thus which characteristics) are most responsible for the rejection. By isolating those characteristics that are a wedge between expected stock returns and exposures to aggregate risk factors, we can work toward an economic understanding of how the wedge emerges.

We construct a Wald-type test statistic for the distance between the restricted and unrestricted models as the sum of squared elements in the estimated  $\Gamma_\alpha$  vector,

$$W_\alpha = \hat{\Gamma}'_\alpha \hat{\Gamma}_\alpha.$$

We conduct inference for this test via bootstrap. Inference proceeds in the following steps. First, we estimate the unrestricted model and, following equation (13), define the estimated model parameters and residuals in the space of managed portfolios as

$$\hat{\Gamma}_\alpha, \hat{\Gamma}_\beta, \{\hat{f}_t\}_{t=1}^T, \text{ and } \{\hat{d}_{l,t}\}_{l=1,t=1}^{L,T}.$$

Next, for  $b = 1, \dots, 50000$ , we generate the  $b^{th}$  bootstrap sample of returns as

$$\tilde{x}_t^b = \hat{\Gamma}_\beta \hat{f}_t + \tilde{d}_t^b, \quad \tilde{d}_t^b = q_1^b \hat{d}_{q_2^b}.$$
(17)

The variable  $q_2^b$  is a list of  $L$  random indices drawn uniformly from the set of all possible data

point indices. In addition, we multiply each residual draw by a Student  $t$  random variable,  $q_1^b$ , that has unit variance and five degrees of freedom. Then, using this bootstrap sample, we re-estimate the unrestricted model and record the estimated test statistic  $\tilde{W}_\alpha^b = \tilde{\Gamma}_\alpha^b \tilde{\Gamma}_\alpha^b$ . Finally, we draw inferences from the empirical null distribution by calculating a  $p$ -value as the fraction of bootstrapped  $\tilde{W}_\alpha^b$  statistics that exceed the value of  $W_\alpha$  from the actual data.

#### 4.1.1 Comments on Bootstrap Procedure

The method described above is a “residual” bootstrap. It uses the model’s structure to generate pseudo-samples under the null hypothesis that  $\Gamma_\alpha = 0$ . In particular, it fixes the explained variation in returns at their estimated common factor values under the null model,  $\hat{\Gamma}_\beta \hat{f}_t$ , and randomizes around the null model by sampling from the empirical distribution of residuals to preserve their properties in the simulated returns data. Because the estimated unrestricted model allows non-zero  $\hat{\Gamma}_\alpha$ , the estimated residuals  $\hat{d}_{l,t}$  have zero mean by construction and, in turn, the bootstrap data set  $x_t^b$  satisfies  $\Gamma_\alpha = 0$  by construction. This approach produces an empirical distribution of  $\tilde{W}_\alpha^b$  designed to quantify the amount of sampling variation in the test statistic  $W_\alpha$  under the null. In Appendix A, we report a variety of Monte Carlo experiments illustrating the accuracy of the test in terms of size (appropriate rejection rates under the null) and power (appropriate rejection rates under the alternative).

Premultiplying the residual draws by a random  $t$  variable is a technique known as the “wild” bootstrap. It is designed to improve the efficiency of bootstrap inference in heteroskedastic data such as stock returns (Goncalves and Killian, 2004). Appendix A also demonstrates the improvement in test performance, particularly power for nearby alternatives, from using a wild bootstrap.

Equation (8) illustrates why we bootstrap data sets of managed portfolios returns,  $x_t$ , rather than raw stock returns,  $r_t$ . Given the definition of the IPCA model, the estimation objective ultimately takes as data the managed portfolio returns,  $x_t = Z_t' r_t$ , and estimates parameters from their covariance matrix. If we were to resample stock returns, the estimation procedure nonetheless converts these into managed portfolios before estimating model parameters. This makes it possible to quantify the sampling variation of the test statistic by resampling  $x_t$  directly. Bootstrapping managed portfolio returns comes with a number of practical advantages. It resamples in a lower dimension setting ( $T \times L$ ) than stock returns ( $T \times N$ ), which reduces computation cost. It also avoids issues with missing observations that exist in the stock panel, but not in the portfolio panel.

Our test enjoys the usual benefits of bootstrapping, such as reliability in finite samples and validity under weak assumptions on residual distributions. Since the estimate of  $\Gamma_\alpha$  operates somewhat like a pooled regression coefficient, it is reasonable to presume it has a well-behaved limiting distribution that the bootstrap captures. It is important to point out that our bootstrap tests are feasible *only* because of the fast analytic estimator that we have derived for IPCA. Estimation of the model via numerical optimization would not only make it very costly to use IPCA in large systems—it would immediately take bootstrapping off the table as a viable testing approach.

## 4.2 Testing Observable Factor Models Versus IPCA

Next, we develop tests that compares IPCA to commonly studied models with pre-specified, observable factors. These tests work in the space of  $L$  managed portfolios and nest IPCA and observable factors in an encompassing model:

$$x_t = \Gamma_\beta f_t + \Psi g_t + d_t. \quad (18)$$

The first term on the right side is the IPCA latent factor specification following equation (13). The second term is the portion of returns described by observable factors, where  $g_t$  denote the  $M \times 1$  vector of observable factor realizations and  $\Psi$  is the  $L \times M$  associated matrix of loadings. The encompassing model imposes the zero alpha restriction so that we can evaluate the ability of competing models to price assets based on exposures to systematic risk.

We are interested in testing the incremental contribution of observable factors after controlling for the IPCA model with two different tests.

### 4.2.1 Realized Return Variation

The first assesses the incremental benefit of observable factors for explaining the total realized variation in returns. The hypotheses for this test are

$$H_0 : \Psi = \mathbf{0}_{L \times M} \quad \text{vs.} \quad H_1 : \Psi \neq \mathbf{0}_{L \times M}.$$

To conduct this test we estimate model (18) in two steps. In Step A, we estimate the IPCA portion of the model,

$$x_t = \Gamma_\beta f_t + d_{A,t}. \quad (19)$$

Step B, using the estimated residuals of (19), estimates the incremental observable factor model via the time series regression:

$$\hat{d}_{A,t} = \Psi g_t + d_{B,t}. \quad (20)$$

We denote the estimated coefficients and residuals as  $\hat{\Psi}$  and  $\hat{d}_{B,t}$ , and we construct the Wald-like test statistic

$$W_{\Psi} = \text{vec}(\hat{\Psi})' \text{vec}(\hat{\Psi}).$$

We estimate  $p$ -values for the test using the same residual wild bootstrap concept from preceding sections. First, for each iteration  $b$ , resample  $\hat{d}_{A,t}$  imposing the null hypothesis:  $\tilde{d}_{A,t}^b = \tilde{d}_{B,t}^b$ , where  $\tilde{d}_{B,t}^b$  is a random draw from  $\{\hat{d}_{B,t}\}_{\tau=1}^T$  scaled by a random  $t$ -distributed variable. Next, from the bootstrap data  $\tilde{d}_{A,t}^b$ , we re-estimate  $\Psi$  in regression (20). Finally, we construct each bootstrap sample's Wald-like test statistic  $\tilde{W}_{\Psi}^b$  and compute the  $p$ -value as the fraction of samples for which  $\tilde{W}_{\Psi}^b$  exceeds  $W_{\Psi}$ .

#### 4.2.2 Average Returns

The next test investigates whether loadings on observable factors have incremental explanatory power for differences in average returns across portfolios. It extends Steps A and B with a further Step C that estimates incremental risk prices for observable factors,  $\lambda_g$ , with a cross-sectional regression:

$$\bar{d}_A = \hat{\Psi} \lambda_g + \delta, \quad (21)$$

where  $\bar{d}_A$  is the  $L \times 1$  the time series average of  $\hat{d}_{A,t}$  and  $\delta$  is the vector of regression residuals. In other words,  $\bar{d}_A$  is the portion of average returns on characteristic-managed portfolios unexplained by IPCA, and  $\lambda_g$  measures how effective observable factors are in explaining IPCA's mispricings. The hypotheses for this test are

$$H_0 : \lambda_g = \mathbf{0}_{M \times 1} \quad \text{vs.} \quad H_1 : \lambda_g \neq \mathbf{0}_{M \times 1}.$$

This test differs from the previous test in that it allows for non-zero  $\Psi$ .  $H_0$  thus states that, even if  $g_t$  helps explain return variation, this variation does not account for differences in average returns above and beyond IPCA.

Let  $\hat{\lambda}_g$  and  $\hat{\delta}$  denote the estimated coefficients and residuals for regression (21). The test statistic is

$$W_{\lambda} = \hat{\lambda}_g' \hat{\lambda}_g.$$

Our residual bootstrap for this test proceeds as follows. For each iteration  $b$ , resample  $\bar{d}_A$  imposing the null hypothesis:  $\tilde{d}_A^b = \tilde{\delta}^b$ , with  $\tilde{\delta}^b$  a randomization of  $\hat{\delta}$ .<sup>9</sup> Next, re-estimate  $\lambda_g$  from resampled data. Finally, construct test statistic  $\tilde{W}_\lambda^b$  and compute the  $p$ -value as the fraction of these that exceed  $W_\lambda$ .

### 4.3 Testing Instrument Significance

Our tests for the significance of an individual characteristic (while simultaneously controlling for all other characteristics) use the same residual bootstrap concept described above. In Kelly, Pruitt and Su (2017) we show that the estimate of  $\Gamma_\beta$  has a well-behaved (Gaussian) limiting distribution, which suggests that the bootstrap will work well. We focus on the zero alpha model in equation (4) to specifically investigate whether a given instrument significantly contributes to  $\beta_{i,t}$ .

To formulate the hypotheses, we partition the parameter matrix as

$$\Gamma_\beta = [\gamma_{\beta,1} , \dots , \gamma_{\beta,L}]'$$

where  $\gamma_{\beta,l}$  is a  $K \times 1$  vector that maps characteristic  $l$  to each loading on the  $K$  factors. Let the  $l^{th}$  element of  $z_{i,t}$  be the characteristic in question. The hypotheses that we test are then

$$H_0 : \Gamma_\beta = [\gamma_{\beta,1} , \dots , \gamma_{\beta,l-1} , \mathbf{0}_{K \times 1} , \gamma_{\beta,l+1} , \dots , \gamma_{\beta,L}]' \quad \text{vs.} \quad H_1 : \Gamma_\beta = [\gamma_{\beta,1} , \dots , \gamma_{\beta,L}]' .$$

The statement of the null hypothesis in  $H_0$  comes from the fact that, for the  $l^{th}$  characteristic to have zero contribution to the model, it cannot impact *any* of the  $K$  factor loadings. In this case, the entire  $l^{th}$  row of  $\Gamma_\beta$  must be zero.

We estimate an alternative model that incorporates the characteristic being evaluated, then we assess whether the distance between the estimate of vector  $\gamma_{\beta,l}$  and zero is statistically large. Our Wald-type statistic in this case is

$$W_{\beta,l} = \hat{\gamma}'_{\beta,l} \hat{\gamma}_{\beta,l}.$$

Inference for this test proceeds by first estimating the model that includes the characteristic in question. We define the estimated model parameters and residuals in the space of managed

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<sup>9</sup>Because these are average returns, we do not use the wild bootstrap scaling as in previous tests. Adding a wild scaling has effectively zero impact on our results.

portfolios as

$$\{\hat{\gamma}_{\beta,l}\}_{l=1}^L, \{\hat{f}_t\}_{t=1}^T, \text{ and } \{\hat{d}_{l,t}\}_{l=1,t=1}^{L,T}.$$

Next, for  $b = 1, \dots, 50000$ , we generate the  $b^{th}$  bootstrap sample of returns under the null hypothesis that the  $l^{th}$  characteristic has no effect on loadings. To do so, we construct the matrix

$$\tilde{\Gamma}_\beta = [\hat{\gamma}_{\beta,1}, \dots, \hat{\gamma}_{\beta,l-1}, \mathbf{0}_{K \times 1}, \hat{\gamma}_{\beta,l+1}, \dots, \hat{\gamma}_{\beta,L}]$$

and re-sample characteristic-managed portfolio returns as

$$\tilde{x}_t^b = \tilde{\Gamma}_\beta \hat{f}_t + \tilde{d}_t^b$$

with the same formulation of  $\tilde{d}_t^b$  used in equation (17). Then, for each sample  $b$ , we re-estimate the alternative model and record the estimated test statistic  $\tilde{W}_{\beta,l}^b = \hat{\gamma}_{\beta,l}'^b \hat{\gamma}_{\beta,l}^b$ . Finally, calculate the test's  $p$ -value as the fraction of bootstrapped  $\tilde{W}_{\beta,l}^b$  statistics that exceed  $W_{\beta,l}$ . This test can be extended to evaluate the joint significance of multiple characteristics  $l_1, \dots, l_J$  by modifying the test statistic to  $W_{\beta,l_1,\dots,l_J} = \hat{\gamma}_{\beta,l_1}' \hat{\gamma}_{\beta,l_1} + \dots + \hat{\gamma}_{\beta,l_J}' \hat{\gamma}_{\beta,l_J}$ .

## 5 Empirical Findings

### 5.1 Data

Our stock returns and characteristics data are from Freyberger, Neuhierl, and Weber (2017). The sample begins in July 1962, ends in May 2014, and includes 12,813 firms. For each firm we have 36 characteristics. They are market beta (**beta**), assets-to-market (**a2me**), total assets (**log\_at**), sales-to-assets (**ato**), book-to-market (**beme**), cash-to-short-term-investment (**c**), capital turnover (**cto**), capital intensity (**d2a**), ratio of change in property/plant/equipment to change in total assets (**dpi2a**), earnings-to-price (**e2p**), fixed costs-to-sales (**fc2y**), cash flow-to-book (**free\_cf**), idiosyncratic volatility (**idio\_vol**), investment (**investment**), leverage (**lev**), log lagged size (**log\_lme**), lagged turnover (**lturnover**), net operating assets (**noa**), operating accruals (**oa**), operating leverage (**ol**), price-to-cost margin (**pcm**), profit margin (**pm**), gross profitability (**prof**), Tobin's Q (**q**), closeness to relative high price (**rel\_high**), return on net operating assets (**rna**), return on assets (**roa**), return on equity (**roe**), momentum (**mom\_12\_2**), intermediate momentum (**mom\_12\_7**), short-term reversal (**mom\_2\_1**), long-term reversal (**mom\_36\_13**), sales-to-price (**s2p**), SG&A-to-sales (**sga2s**), bid-ask spread (**spread**), and unexplained volume (**suv**). We restrict attention to  $(i, t)$  observations for

which all 36 characteristics and the next month return are non-missing. For further details and summary statistics, see Freyberger, Neuhierl, and Weber (2017).

These characteristics vary both in the cross section and over time. The two dimensions potentially aid IPCA’s estimation of the factor model in different ways. For example, the average level of a stock characteristic may be helpful for understanding a stock’s unconditional factor loadings, while time variation around this mean may help understand the stock’s conditional loadings. The relevance of the two components for asset pricing may differ. To allow for this, we separate all characteristics into their time series mean and their deviation around the mean. We denote the vector of characteristics on stock  $i$  at time  $t$  as  $c_{i,t}$ . The vector of IPCA instruments includes both the means and deviations as

$$\tilde{z}_{i,t} = (\bar{c}'_i, c'_{i,t} - \bar{c}'_i)', \quad \text{where} \quad \bar{c}_i \equiv \frac{1}{T} \sum_{t=1}^T c_{i,t}.$$

When we perform out-of-sample analyses, we replace the full sample mean  $\bar{c}_i$  with the historical mean  $\bar{c}_{i,t} \equiv \frac{1}{t} \sum_{\tau=1}^t c_{i,\tau}$ . Similar to Asness et al. (2014), Freyberger et al. (2017), and Kozak et al. (2017), we perform a rank transformation of these instruments to the unit interval.

The convenience of the IPCA estimator exploits orthonormality of the instruments, as discussed in Section 3. To achieve cross-sectional orthonormality in each period, we convert  $\tilde{z}_{i,t}$  into  $z_{i,t}$  by sequentially orthogonalizing instruments in the cross section using the Gram-Schmidt process, and then cross-sectionally variance standardizing the result.

This orthogonalization is not invariant to the ordering of characteristics. As a result, our tests of individual characteristics can be influenced by the order of the instruments. We choose an instrument ordering on economic grounds. In particular, characteristics are arranged within  $z_{i,t}$  according to the date that the proposed characteristic effect was published. Thus market beta is ordered first, size second, and so forth as described in Appendix B. Appendix B also demonstrates the robustness of our results and conclusions to alternative instrument orderings. It is possible to orthonormalize instruments in an order invariant way, such as using a cross-sectional eigenvector decomposition of characteristics. While this produces very similar results in terms of model fits, it destroys interpretability of characteristics. Publication ordering redefines each instrument as the component of a characteristic that is orthogonal to all characteristics published before it.



## 5.2 The Asset Pricing Performance of IPCA

We estimate the  $K$ -factor IPCA model for various choices of  $K$ , and consider both restricted ( $\Gamma_\alpha = \mathbf{0}_{L \times 1}$ ) and unrestricted versions of each specification. Two  $R^2$  statistics measure model performance. The first we refer to as the total  $R^2$  and define it as

$$\text{Total } R^2 = 1 - \frac{\sum_{i,t} \left( r_{i,t} - z'_{i,t-1} \hat{\Gamma}_\alpha - z'_{i,t-1} \hat{\Gamma}_\beta \hat{f}_t \right)^2}{\sum_{i,t} r_{i,t}^2}. \quad (22)$$

It represents the fraction of return variance explained by both the dynamic behavior of conditional loadings (and alphas in the unrestricted model), as well as by the contemporaneous factor realizations, aggregated over all assets and all time periods. The total  $R^2$  summarizes how well the systematic factor risk in a given model specification describes the total realized riskiness in the panel of individual stocks.

The second measure we refer to as the “predictive  $R^2$ ” and define it as

$$\text{Predictive } R^2 = 1 - \frac{\sum_{i,t} \left( r_{i,t} - z'_{i,t-1} \hat{\Gamma}_\alpha - z'_{i,t-1} \hat{\Gamma}_\beta \hat{\lambda} \right)^2}{\sum_{i,t} r_{i,t}^2}. \quad (23)$$

It represents the fraction of realized return variation explained by the model’s description of conditional expected returns. IPCA’s return predictions are based on dynamics in factor loadings (and alphas in the unrestricted model). In theory, expected returns can also vary because risk prices vary. One limitation of IPCA is that, without further model structure, it cannot separately identify risk price dynamics. Hence, we hold estimated risk prices constant and predictive information enters return forecasts only through the instrumented loadings. When the  $\Gamma_\alpha = \mathbf{0}_{L \times 1}$  is imposed, the predictive  $R^2$  summarizes the model’s ability to describe risk compensation with exposure to systematic risk. For the unrestricted model, the predictive  $R^2$  describes how well characteristics explain expected returns in any form—be it through loadings or through anomaly intercepts.

Panel A of Table I reports  $R^2$ ’s at the individual stock level for  $K = 1, \dots, 6$  factors. With a single factor, the restricted ( $\Gamma_\alpha = \mathbf{0}$ ) IPCA model explains 14.6% of the total variation in stock returns. Allowing for non-zero  $\Gamma_\alpha \neq \mathbf{0}$  increases the total  $R^2$  by 1.1 percentage points to 15.7%. As a reference point, the one-factor market model total  $R^2$  is 11.9% in the same sample.

The predictive  $R^2$  in the restricted one-factor model is 0.5%. This is for individual stocks

**Table I**  
**IPCA Model Performance**

**Note.** Panel A and B report total and predictive  $R^2$  in percent for the restricted ( $\Gamma_\alpha = \mathbf{0}$ ) and unrestricted ( $\Gamma_\alpha \neq \mathbf{0}$ ) IPCA model. These are calculated with respect to either individual stocks (Panel A) or characteristic-managed portfolios (Panel B). Panel C reports the  $W_\alpha$  test statistic value as a percentage of the magnitude of mean portfolio returns, the corresponding percentage  $R^2$  from regressing by  $\bar{x}$  on  $\Gamma_\beta$ , and the bootstrapped  $p$ -value of the test that  $\Gamma_\alpha = \mathbf{0}$ .

		$K$					
		1	2	3	4	5	6
Panel A: Individual Stocks ( $r_t$ )							
Total $R^2$	$\Gamma_\alpha = \mathbf{0}$	14.6	16.3	17.7	18.5	19.2	19.5
	$\Gamma_\alpha \neq \mathbf{0}$	15.7	16.8	17.8	18.6	19.2	19.5
Pred. $R^2$	$\Gamma_\alpha = \mathbf{0}$	0.46	1.12	1.46	1.51	1.54	1.55
	$\Gamma_\alpha \neq \mathbf{0}$	1.55	1.55	1.55	1.55	1.55	1.55
Panel B: Managed Portfolios ( $x_t$ )							
Total $R^2$	$\Gamma_\alpha = \mathbf{0}$	62.2	68.6	73.2	76.3	78.7	80.0
	$\Gamma_\alpha \neq \mathbf{0}$	66.1	70.1	73.6	76.5	78.7	80.0
Pred. $R^2$	$\Gamma_\alpha = \mathbf{0}$	1.82	4.12	5.34	5.52	5.63	5.63
	$\Gamma_\alpha \neq \mathbf{0}$	5.67	5.67	5.67	5.67	5.67	5.67
Panel C: Asset Pricing Test ( $W_\alpha$ )							
$100 \times W_\alpha / \ \bar{x}\ ^2$		66.8	26.3	5.81	2.55	0.62	0.59
C.S. $R^2$		33.2	73.7	94.2	97.4	99.4	99.4
$p$ -value		0.00	1.78	22.7	31.8	33.9	28.6

and at the monthly frequency. To benchmark this magnitude, the predictive  $R^2$  from the Fama-French three-factor model is 0.3% in a matched individual stock sample.

In the unrestricted one-factor model, the predictive  $R^2$  is 1.6% per month for individual stocks. IPCA exhaustively attributes all predictive content from characteristics to either betas or alphas. That is, the unrestricted predictive  $R^2$  is equal to the predictive  $R^2$  from direct regression of returns onto lagged characteristics with panel OLS regression. This why the predictive  $R^2$  value does not vary across choices of  $K$ . Increasing  $K$  only changes the fraction of characteristic predictive power that can be mapped into factor loadings.

The restricted  $K = 1$  model therefore captures roughly 30% of the return predictability embodied by characteristics. While 0.5% is an economically large  $R^2$  for monthly stock prediction, that IPCA one-factor loadings miss 70% of characteristics-based predictability suggests economically large values of  $\Gamma_\alpha$  for  $K = 1$ . This failure of the restricted  $K = 1$  IPCA

model is statistically borne out by the hypothesis test of  $\Gamma_\alpha = \mathbf{0}$  in Panel C. The test statistic,  $W_\alpha$ , is the sum of squared elements of  $\Gamma_\alpha$ . To interpret the magnitude of the test statistic, we report it as a percentage of squared average portfolio returns,  $100 \times W_\alpha / \|\bar{x}\|^2$ . The cross section regression of  $\bar{x}$  on  $\hat{\Gamma}_\beta$  in equation (15), which quantifies the relative magnitude of IPCA pricing errors for characteristic-managed portfolios, is equal to

$$\text{C.S. } R^2 = 1 - W_\alpha / \|\bar{x}\|^2$$

and is also reported. For  $K = 1$ , 66.8% of cross section variation in average portfolio returns is unexplained by IPCA, thus the test rejects  $\Gamma_\alpha = \mathbf{0}$  with a  $p$ -value below 0.1%.

When we allow for multiple IPCA factors, the gap between restricted and unrestricted models shrinks rapidly. At  $K = 3$ , the total  $R^2$  for the restricted model is 17.7%, thus achieving more than 99% of the explanatory power of the unrestricted model. The predictive  $R^2$  rises to 1.5%, capturing 94% of all characteristics' predictive content while imposing  $\Gamma_\alpha = \mathbf{0}$ . The magnitude of the test statistic drops dramatically, as the restricted  $K = 3$  IPCA model leaves only to 5.8% of variation in  $\bar{x}$  unexplained. The test fails to reject the null hypothesis that  $\Gamma_\alpha = \mathbf{0}$  by a large margin ( $p$ -value of 22.7%). The results for  $K > 3$  are quantitatively similar.

This result says that, with  $K \geq 3$  factors, IPCA explains essentially all of the heterogeneity in average stock returns associated with stock characteristics. It does so by identifying a set of factors and associated loadings such that stocks' expected returns align with their exposures to systematic risk—without resorting to alphas to explain the predictive role of characteristics. In other words, IPCA infers that characteristics are risk exposures, not anomalies.

Note that, because IPCA is estimated from a least squares criterion, it directly targets total  $R^2$ . Thus the risk factors that IPCA identifies are optimized to describe the systematic risks among stocks. They are by no means specialized to explain average returns, however, as estimation does not directly target the predictive  $R^2$ . Because conditional expected returns are a small portion of total return variation (as evidenced by the 1.6% predictive  $R^2$  in the unrestricted model), it is very well possible that a misspecified model could provide an excellent description of risk yet a poor description of risk compensation. Evidently, this is not the case for IPCA, as its risk factors indirectly produce an accurate description of risk compensation across assets.

The asset pricing literature is accustomed to evaluating the performance of pricing factors in explaining the behavior of test portfolios, such as the 5×5 size and value-sorted portfolios

of Fama and French (1993), as opposed to individual stocks. The behavior of portfolios can differ markedly from individual stocks because a large amount of idiosyncratic stock behavior is averaged out. As emphasized in Section 3.1.1, IPCA asset pricing tests can be equivalently interpreted as tests of stocks or of a particular set of characteristic-managed portfolios. In this spirit, Panel B of Table I evaluates fit measures for managed portfolios,  $x_t$ .<sup>10</sup> With  $K = 3$  factors, the total  $R^2$ 's for the restricted and unrestricted models are 73.2% and 73.6%, respectively. Indeed, systematic risk explains three-fourths of total variation in portfolio returns. The reduction in noise via portfolio formation also improves predictive  $R^2$ 's to 5.3% and 5.7%, respectively.

### 5.3 Comparison with Observable Factors

The results in Table I compare the performance of IPCA across specification choices for  $K$  and with or without imposition of asset pricing restrictions. We now compare IPCA to leading alternative modeling approaches in the literature. The first includes models with pre-specified observable factors. We consider models with  $K = 1, 3, 4, 5$ , or 6 observable factors. The  $K = 1$  model is the CAPM (using the CRSP value-weighted excess market return as the factor), the  $K = 3$  model is the Fama-French (1993) three-factor model that includes SMB and HML ("FF3" henceforth) with the market. The  $K = 4$  model is the Carhart (1997, "FFC4") model that adds MOM to the FF3 model.  $K = 5$  is the Fama-French (2015, "FF5") five-factor model that adds RMW and CMA to the FF3 factors. Finally, we consider a six-factor model ("FFC6") that includes MOM alongside the FF5 factors.

The second set of alternatives are static latent factor models estimated with PCA. In this approach, we consider one to six principal component factors from the panel of individual stock returns.

We estimate all models in Table II restricting intercepts to zero. For IPCA, we do so imposing  $\Gamma_\alpha = \mathbf{0}$ . For the observable factor models, we estimate stock-by-stock time series regressions via OLS omitting a constant. For static latent factor models, we estimate PCA from uncentered stocked returns. This forces a stock's average return to equal its static factor loading times the factors' time series average, exactly mirroring our estimation of the

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<sup>10</sup>Fit measures for  $x_t$  are

$$\text{Total } R^2 = 1 - \frac{\sum_t (x_t - \hat{\Gamma}_\alpha - \hat{\Gamma}_\beta \hat{f}_t)' (x_t - \hat{\Gamma}_\alpha - \hat{\Gamma}_\beta \hat{f}_t)}{\sum_t x_t' x_t}, \text{ Predictive } R^2 = 1 - \frac{\sum_t (x_t - \hat{\Gamma}_\alpha - \hat{\Gamma}_\beta \hat{\lambda})' (x_t - \hat{\Gamma}_\alpha - \hat{\Gamma}_\beta \hat{\lambda})}{\sum_t x_t' x_t}.$$

**Table II**  
**IPCA Comparison With Observable Factors**

**Note.** The table reports total and predictive  $R^2$  in percent and number of estimated parameters ( $N_p$ ) for the restricted ( $\Gamma_\alpha = \mathbf{0}$ ) IPCA model (Panel A), for observable factor models (Panel B), and for static latent factor models (Panel D). Observable factor models specifications are:  $K = 1$  MKT-RF;  $K = 3$  (MKT-RF,SMB,HML);  $K = 4$  (MKT-RF,SMB,HML,MOM);  $K = 5$  (MKT-RF,SMB,HML,RMW,CMA);  $K = 6$  (MKT-RF,SMB,HML,RMW,CMA,MOM). Panel C reports tests of the incremental explanatory power of each observable factor model with respect to the  $K = 3$  IPCA model. Incremental total  $R^2$  is the percentage of total portfolio variation explained by observable factors after controlling for  $K = 3$  IPCA. Incremental C.S.  $R^2$  is the percentage of cross-sectional variation in average portfolio returns explained by observable factors after controlling for  $K = 3$  IPCA.

Test Assets	Statistic	$K$				
		1	3	4	5	6
Panel A: IPCA						
$r_t$	Total $R^2$	14.8	17.8	18.6	19.3	19.6
	Pred. $R^2$	0.47	1.42	1.47	1.50	1.51
	$N_p$	671	2013	2684	3355	4026
$x_t$	Total $R^2$	62.2	73.2	76.3	78.7	80.0
	Pred. $R^2$	1.82	5.34	5.52	5.63	5.63
	$N_p$	671	2013	2684	3355	4026
Panel B: Observable Factors						
$r_t$	Total $R^2$	11.9	18.9	20.9	21.9	23.7
	Pred. $R^2$	0.31	0.29	0.28	0.29	0.23
	$N_p$	11452	34356	45808	57260	68712
$x_t$	Total $R^2$	45.4	60.4	62.8	62.3	64.5
	Pred. $R^2$	1.28	1.92	1.84	2.31	2.16
	$N_p$	72	216	288	360	432
Panel C: Test of IPCA vs. Observable Factors						
	$W_\Psi$ $p$ -value	80.5	0.01	0.00	0.01	0.03
	$W_\lambda$ $p$ -value	0.01	0.00	0.00	0.00	0.00
	Incremental Total $R^2$	0.02	0.71	1.78	1.01	2.04
	Incremental C.S. $R^2$	0.56	2.09	2.13	2.12	2.16
Panel D: Principal Components						
$r_t$	Total $R^2$	16.8	26.2	29.0	31.5	33.8
	Pred. $R^2$	$< 0$	$< 0$	$< 0$	$< 0$	$< 0$
	$N_p$	13412	40236	53648	67060	80472

restricted IPCA model.<sup>11</sup>

<sup>11</sup>In calculating PCA, we confront the fact that the panel of returns is unbalanced. Therefore, we must estimate PCA using an alternating least squares EM algorithm as described by Stock and Watson (2002b).

Table II reports the total and predictive  $R^2$  as well as the number of estimated parameters ( $N_p$ ) for each model.<sup>12</sup> For ease of comparison, Panel A report model fit results for IPCA with  $\Gamma_\alpha = \mathbf{0}$ .<sup>13</sup> Panel B reports fits for the observable factor models (CAPM through FFC6). In the analysis of individual stocks, observable factor models generally produce a slightly higher total  $R^2$  than the IPCA specification using the same number of factors. For example, at  $K = 3$ , FF3 achieves a 1.1 percentage point improvement in  $R^2$  relative to IPCA’s fit of 17.8%. To accomplish this, however, observable factors rely on vastly more parameters than IPCA. The number of parameters in an observable factor model is equal to the number of loadings, or  $N_p = NK$ . For IPCA, the number of factors is the dimension of  $\Gamma_\beta$  plus the number of estimated factor realizations, or  $N_p = LK + TK$ . In our sample of 11,452 stocks with 72 instruments over 599 months, observable factor models therefore estimate 17 times ( $\approx 11452/(72 + 599)$ ) as many parameters as IPCA.<sup>14</sup> In short, IPCA provides a similar description of systematic risk in individual stock returns as the leading observable factors while using almost 95% fewer parameters.

At the same time, IPCA provides a substantially more accurate description of stocks’ risk compensation than observable factor models, as evidenced by the predictive  $R^2$ . Observable factor models’ predictive power never rises beyond 0.3% for any specification, only a fifth of the 1.4% predictive  $R^2$  from IPCA with  $K = 3$ .

Among  $x_t$ , observable factor models’ total  $R^2$  suffers in comparison to IPCA. At  $K = 3$ , IPCA explains 73.2% of total portfolio return variation while FF5 explains 62.3%. IPCA ( $K = 3$ ) more than doubles the predictive  $R^2$  of FF5, at 5.3% versus 2.3%. When test assets are managed portfolios, IPCA dominates in its ability to describe systematic risks as well as cross-sectional differences in average returns.

As a practical matter, this means that PCA estimation for individual stocks bears a high computational cost. It also highlights the computational benefit of IPCA, which side steps the unbalanced panel problem by parameterizing betas with characteristics and, as a result, is estimated from managed portfolios that can always be constructed to have no missing data.

<sup>12</sup>The  $R^2$ ’s for alternative models are defined analogously to those of IPCA. In particular, for individual stocks they are

$$\text{Total } R^2 = 1 - \frac{\sum_{i,t} (r_{i,t} - \hat{\beta}_i \hat{f}_t)^2}{\sum_{i,t} r_{i,t}^2}, \text{ Predictive } R^2 = 1 - \frac{\sum_{i,t} (r_{i,t} - \hat{\beta}_i \hat{\lambda})^2}{\sum_{i,t} r_{i,t}^2},$$

and are similarly adapted for managed portfolios  $x_t$ . In all cases, model fits are based on exactly matched samples with IPCA.

<sup>13</sup>These differ minutely from Table I results because we drop some stock-month observations for the sake of estimating the observable factor models—see footnote 14.

<sup>14</sup>Because we require at least 60 non-missing months to compute observable factor betas, we filter out slightly more than a thousand stocks compared to the sample used in Table I. As a result, statistics in Tables I and II can differ minutely.

Panel C formally compares of each observable factor model versus IPCA (with  $K = 3$ ) using the tests from Section 4.2. We can easily reject the null of no additional explanatory power from observable factors for all models except the CAPM. Despite this rejection, the incremental benefits of observable factors have small economic magnitudes. The “Incremental Total  $R^2$ ” row describes the fraction of variation in  $x_t$  explained by each observable factor model after controlling for the three-factor IPCA specification.<sup>15</sup> After IPCA explains 73.2% of the panel variation in  $x_t$ , observable factors explain at most another 2.0% (FFC6).<sup>16</sup> We likewise report the “Incremental C.S.  $R^2$ ,” which describes the fraction of variation in  $\bar{x}$  described by observable factor loadings after controlling for IPCA three-factor loadings. IPCA explains 97.4% of the heterogeneity in  $\bar{x}$ , and FFC6 captures an additional 2.1%. In either calculation, the incremental contribution of observable factors is economically small.

In Panel D we report the performance of static latent factor models estimated with PCA. Naturally, in this panel, we report only the analysis for individual stocks (PCA on  $x_t$  is identical to IPCA). For all  $K$ , the total  $R^2$  exceeds that of IPCA and observable factor models. This is expected as PCA directly selects factors and loadings to maximize the explained variance of stock returns and is the least constrained estimator of the three approaches. This is evident in its parameter count,  $N_p = NK + TK$ , which exceeds even that of observable factor models.

While PCA optimizes the in-sample description of systematic risk, it provides a dismal description of risk compensation. The static PCA loadings provide such a poor description of expected returns that the predictive  $R^2$  is negative for every  $K$ . In other words, a static return forecast of zero for all stocks is a better prediction than using the estimated risk loadings from PCA.

## 5.4 Out-of-sample Comparisons

Thus far, the comparison of IPCA and alternatives has been based on in-sample estimates. That is, IPCA and PCA factors and loadings are estimated from the full panel of stock returns, and observable factor loadings are estimated from the full time series. Next we analyze out-of-sample fits from IPCA and observable factor models. Due to the poor in-sample predictive performance of PCA, we exclude it from out-of-sample comparisons.

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<sup>15</sup>Let  $R_{\text{IPCA}}^2$  denote total  $R^2$  for  $x_t$  using the IPCA model. Let  $R_A^2$  denote the regression of IPCA residuals on observable factors in equation (20). The incremental total  $R^2$  due to observable factors as  $(1 - R_{\text{IPCA}}^2)R_A^2$ .

<sup>16</sup>The incremental  $R^2$  is non-monotonic in  $K$  because observable factor specifications are non-nested. FFC4 and FFC6 include MOM, while FF5 does not. The size of the non-monotonicity indicates that momentum is the most important observable factor in terms of incremental total  $R^2$ .

**Table III**  
**Out-of-sample Fits**

**Note.** The table reports out-of-sample total and predictive  $R^2$  in percent.

Test Assets	Statistic	$K$				
		1	3	4	5	6
Panel A: IPCA						
$r_t$	Total $R^2$	12.2	14.1	14.6	15.1	15.7
	Pred. $R^2$	0.40	0.48	0.50	0.50	0.50
$x_t$	Total $R^2$	50.5	51.7	51.9	52.7	53.4
	Pred. $R^2$	1.75	3.35	3.40	3.46	3.42
Panel B: Observable Factors						
$r_t$	Total $R^2$	8.33	9.65	8.38	7.74	6.55
	Pred. $R^2$	0.26	0.30	0.17	0.21	0.11
$x_t$	Total $R^2$	37.5	49.6	52.8	51.4	54.4
	Pred. $R^2$	1.33	2.31	2.33	2.87	2.81

To construct out-of-sample fit measures, we use recursive backward-looking estimation and track the post-estimation performance of estimated models. In particular, in every month  $t \geq T/2$ , we use all data through  $t$  to estimate the IPCA model and save the estimates  $\hat{\Gamma}_{\beta,t}$  and  $\hat{\lambda}_t$ .<sup>17</sup> Then, based on equation (14), we calculate the out-of-sample realized factor return at  $t+1$  as  $\hat{f}_{t+1,t} = \left(\hat{\Gamma}'_{\beta,t}\hat{\Gamma}_{\beta,t}\right)^{-1}\hat{\Gamma}'_{\beta,t}x_{t+1}$ . That is, IPCA factor returns at  $t+1$  may be calculated with individual stock weights  $\left(\hat{\Gamma}'_{\beta,t}\hat{\Gamma}_{\beta,t}\right)^{-1}\left(\hat{\Gamma}'_{\beta,t}Z'_t\right)$  that require no information beyond time  $t$ , just like the portfolio sorts used to construct observable factors.

The out-of-sample total  $R^2$  compares  $r_{t+1}$  to  $Z_t\hat{\Gamma}_{\beta,t}\hat{f}_{t+1,t}$  and  $x_{t+1}$  to  $\hat{\Gamma}_{\beta,t}\hat{f}_{t+1,t}$ . The out-of-sample predictive  $R^2$  is defined analogously, replacing  $\hat{f}_{t+1,t}$  with  $\hat{\lambda}_t$ . Fit measures for observable factor models are the same with the difference that factor realizations at  $t+1$  do not need to be constructed.

Table III reports out-of-sample  $R^2$  statistics. The main conclusion from the table is that the strong performance of IPCA, both in absolute terms and relative to leading observable factor models, is not merely an in-sample phenomenon driven by statistical overfit. IPCA delivers nearly the same out-of-sample total  $R^2$  that it achieves in-sample. And while the predictive  $R^2$  is noticeably reduced, it remains economically large and outperforms the predictions from observable factors, for both individual stocks and managed portfolios.

<sup>17</sup>Hence, our out-of-sample period begins in mid-1989.



**Table IV**  
**Out-of-Sample Factor Portfolio Efficiency**

**Note.** The table reports out-of-sample annualized Sharpe ratios for individual factors (“univariate”) and for the mean-variance efficient portfolio of factors in each model (“tangency”).

	$K$					
	1	2	3	4	5	6
Panel A: IPCA						
Univariate	0.64	0.83	0.58	0.37	0.47	0.14
Tangency	0.64	0.96	1.31	1.57	1.75	2.15
Panel B: Observable Factors						
Univariate	0.49	0.19	0.25	0.49	0.48	0.42
Tangency	0.49	0.35	0.52	0.68	0.91	0.96

## 5.5 Factor Efficiency

Zero intercepts in a factor pricing model are equivalent to multivariate mean-variance efficiency of the factors. This fact is the basis for the Gibbons, Ross, and Shanken (1989) alpha test and bears a close association with our  $W_\alpha$  test. The evidence thus far indicates that IPCA describes expected asset returns more accurately than competing factor models both in-sample and out-of-sample, suggesting that IPCA factors achieve higher multivariate efficiency than competitors. In this section, we directly investigate factor efficiency in terms of annualized Sharpe ratios.

Kozak, Nagel, and Santosh (forthcoming) emphasize that higher-order principal components of “anomaly” portfolios tend to be overfit and generate unreasonably high in-sample Sharpe ratios. In light of this, we focus our analysis on out-of-sample IPCA factor returns. We report univariate Sharpe ratios to describe individual factor efficiency. To describe multivariate efficiency, we report the tangency portfolio Sharpe ratio for a group of factors. We calculate out-of-sample factor returns following the same recursive estimation approach from Section 5.3. The tangency portfolio return for a set of factors is also constructed on a purely out-of-sample basis by using the mean and covariance matrix of estimated factors through  $t$  and tracking the post-formation  $t + 1$  return.

Out-of-sample IPCA Sharpe ratios are shown in Panel A of Table IV. The  $k^{th}$  column reports the univariate Sharpe ratio for factor  $k$  as well as the tangency Sharpe ratio based on factors 1 through  $k$ . For comparison, we report Sharpe ratios of observable factor models in Panel

**Table V**  
**Characteristic Significance**

**Note.** Percentage  $p$ -values for characteristic significance based on the test of Section 4.3. Significance at the 1% level accompanied by \*\* and at the 5% level by \*.

beta	0.00**	lturnover	6.10	ol	8.60
size	0.01**	noa	19.9	c	25.8
e2p	0.00**	rel_high	3.12*	mom_12_7	32.1
beme	0.00**	idio_vol	1.52*	spread	13.3
q	15.9	ato	15.2	at	15.2
mom_36_13	11.2	dpi2a	34.0	lev	18.4
a2me	0.70**	investment	20.3	prof	22.8
mom_1_0	0.00**	pm	28.4	s2p	8.49
cto	23.4	rna	37.9	sga2m	23.2
oa	22.5	suv	0.51**	d2a	30.1
roe	20.5	roa	30.3	fc2y	32.3
mom_12_2	46.1	free_cf	18.7	pcm	15.8

B.<sup>18</sup> The first IPCA factor produces a Sharpe ratio of 0.64, versus 0.49 for the market over the same out-of-sample period.<sup>19</sup> The second IPCA factor has the highest individual out-of-sample Sharpe ratio at 0.83, and boosts the Sharpe ratio for tangency portfolio to 0.96. Adding additional factors increases the tangency Sharpe ratio further, reaching as high as 2.15 for  $K = 6$ . For our preferred IPCA model with  $K = 3$ , the tangency Sharpe ratio is 1.31. It is interesting to note how near this falls to the value of  $\sqrt{2}$  that Kozak et al. (forthcoming) conclude is a plausible maximum Sharpe ratio based on a related cross section of anomaly return portfolios. The out-of-sample Sharpe ratios of IPCA factors exceed those of observable factor models such as the FF5 model, which itself reaches an impressive tangency Sharpe ratio of 0.96.

## 5.6 Which Characteristics Matter?

Our statistical framework allows us to address questions about the incremental contribution of characteristics to help address the Cochrane (2005) quotation above. We test the

<sup>18</sup>A difference between IPCA and observable factors is that observable factors are pre-constructed on an out-of-sample basis. We construct observable factor tangency portfolios using historical mean and covariance estimates, following the same approach as for IPCA.

<sup>19</sup>The second half of our sample, which corresponds to our out-of-sample evaluation period, was an especially good period for the market in terms of Sharpe ratio. In the full post-1964 sample, the market Sharpe ratio is 0.37.

**Table VI**  
**IPCA Fits Excluding Insignificant Instruments**

**Note.** IPCA percentage  $R^2$  at the individual stock level including only the seven characteristics from Table V that are significant at the 1% level.

		$K$					
		1	2	3	4	5	6
Total $R^2$	$\Gamma_\alpha = \mathbf{0}$	14.3	15.9	17.2	17.9	18.5	18.7
	$\Gamma_\alpha \neq \mathbf{0}$	15.5	16.2	17.3	18.0	18.5	18.7
Pred. $R^2$	$\Gamma_\alpha = \mathbf{0}$	0.47	1.38	1.56	1.58	1.62	1.61
	$\Gamma_\alpha \neq \mathbf{0}$	1.61	1.61	1.61	1.61	1.61	1.61

statistical significance of an individual characteristic while simultaneously controlling for all other characteristics. Each characteristic enters the beta specification through two rows of  $\Gamma_\beta$  matrix: one row corresponding to the average level of the characteristic and the other to deviations around this level. A characteristic is irrelevant to the asset pricing model if all  $\Gamma_\beta$  elements in these two rows are zero. Our tests of characteristic  $l$ 's significance is based on the  $W_\beta$  statistic of Section 4.3 which measures the distance of these two  $\Gamma_\beta$  rows from zero.

Table V reports  $p$ -values for the significance of each characteristic based on this test. Of the 36 characteristics in our sample, only seven are significant at the 1% level: market beta, size, earnings-to-price, book-to-market, assets-to-market, short-term reversal, and unexplained volume. Two more, price relative to its trailing 52-week high and idiosyncratic volatility, are significant at the 5% level.

The insignificance of so many characteristics begs the question of whether the small subset of significant characteristics produces a factor model with similar explanatory power to the 36 characteristics data set. Table VI repeats the IPCA model fit analysis of Table I but instead uses only the seven characteristics that are significant at the 1% level. The seven-characteristic model overall performs very similarly to the model with all 36 characteristics. For  $K = 3$ , the total  $R^2$  in the  $\Gamma_\alpha = \mathbf{0}$  model is 17.2% and 17.8% for seven and 36 characteristics, respectively. And the predictive  $R^2$  improves slightly in the seven-characteristic model from 1.42% to 1.56%.

The results of Table I show that characteristics align with expected returns through their association with risk exposures rather than alphas. Additionally, Table VI suggests that the success of IPCA is obtainable using only a few characteristics, with the others being statistically irrelevant for the model's fit.

### 5.6.1 Static or Dynamic Loadings?

Our definition of  $z_{i,t}$  splits each characteristic into two instruments: its mean and its time series deviation from the mean. We next analyze the relative contribution of these two components to the return factor model. In addition to our main specification in which  $z_{i,t} = (\bar{c}'_i, c'_{i,t} - \bar{c}'_i)'$ , we consider three nested variations of the IPCA model. The first sets instruments equal to the total characteristic value,  $z_{i,t} = c_{i,t}$ . This is equivalent to imposing that the  $\Gamma_\beta$  coefficients corresponding to  $\bar{c}_i$  and  $c_{i,t} - \bar{c}_i$  are equal, and helps answer the question “Do the level and variation in characteristics contribute different information to factor loadings.” If this specification performs as well as our main specification, then level and variation enter  $\beta_{i,t}$  equally and there is no need to split them.

The second variation sets instruments equal to the mean characteristic value,  $z_{i,t} = \bar{c}_i$ . This is equivalent to setting  $\Gamma_\beta$  coefficients on to  $c_{i,t} - \bar{c}_i$  equal to zero. By testing this against our main specification we address the question, “Is a static factor model sufficient for describing returns?,” in which case the benefits of characteristics shown in our preceding results arise from their ability to better differentiate loadings across assets rather than over time. The third variation asks the complementary question, “Is time series variation in characteristics the primary contributor to IPCA success?” In this case we set instruments equal to the deviation value only,  $z_{i,t} = c_{i,t} - \bar{c}_i$ , and fix coefficients on  $\bar{c}_i$  to zero.

Because these comparisons can be formulated as restrictions on rows of  $\Gamma_\beta$ , the model comparison test in Section 4.3 can be used to conduct formal statistical inference for whether our main split-characteristic specification significantly improves over each of the three nested variations.<sup>20</sup>

Table VII reports model fits for each specification. In terms of total  $R^2$ , the nested variation that is closest to our main specification for  $K = 3$  is that using characteristic means,  $z_{i,t} = \bar{c}_i$ . It produces a total  $R^2$  of 16.6%, versus 17.7% in the main model. This suggests that, for the purposes of describing asset riskiness, the unconditional levels of characteristics are nearly as informative as splitting it into its level and variation.

However, the predictive  $R^2$  results show that temporal variation around the mean is the most important characteristic component for describing risk compensation. Conditional expected return estimates from time series variation alone describe 1.2% of total return variance,

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<sup>20</sup>Goyal (2012) notes that “In practice, one almost always employs firm characteristics that vary over time. There are relatively few analytical results in the literature for the case dealing with time-varying characteristics.” The tests we describe in this section provide a means of investigating the role of time-varying characteristics in a fully formulated statistical setting.

**Table VII**  
**Static Versus Dynamic Loadings**

**Note.** Percentage  $R^2$  from IPCA specifications based on either total characteristics, time series mean characteristics, deviations from their mean, or both.

$K$	Total $R^2$				Predictive $R^2$			
	$c$	$\bar{c}$	$c - \bar{c}$	$\bar{c}, c - \bar{c}$	$c$	$\bar{c}$	$c - \bar{c}$	$\bar{c}, c - \bar{c}$
1	13.9	14.1	12.8	14.6	0.33	0.31	0.41	0.46
2	15.1	15.8	14.4	16.3	0.41	0.35	1.08	1.12
3	16.1	16.6	15.2	17.7	0.43	0.41	1.21	1.46
4	16.9	17.1	15.8	18.5	0.46	0.70	1.21	1.51
5	17.6	17.4	16.2	19.2	0.46	0.70	1.21	1.54
6	18.2	17.6	16.5	19.5	0.59	0.71	1.23	1.55

versus 1.5% from the main split-characteristic specification and 0.4% for the  $\bar{c}_i$  specification. Lastly, the statistical test rejects all three nested variations in favor of the more general split-characteristic specification with  $p$ -values below 1%.<sup>21</sup> This is true for all  $K$ . In summary, the data significantly prefer a dynamic factor model over a static one, and the variation in characteristics across assets and over time contribute differently (and both significantly) to the specification of betas.

## 6 Conclusion

Our primary conclusions are three-fold. First, by estimating latent factors as opposed to relying on pre-specified observable factors, we find a three-factor model that is successfully describes riskiness of stock returns (by explaining realized return variation) and risk compensation (by explaining cross section differences in average returns). We show that there are no significant anomaly intercepts associated with a large collection stock characteristics, and instead show that the differences in average returns across stocks align with differences in exposures to our three factors.

Second, our three-factor model outperforms leading observable factor models, such as the Fama-French five-factor model, in delivering small pricing errors. This is true in-sample and out-of-sample. Our factors also achieve a higher level of out-of-sample mean-variance efficiency than alternative models.

<sup>21</sup>We omit percentage  $p$ -values from the table because as they all are zero to two decimal places.

Third, only a small subset of the stock characteristics are responsible for the empirical success of our approach. The remaining 80% of the characteristics in our sample are statistically irrelevant to our factor model. Our tests conclude that the 20% of characteristics that are significant add value by better identifying latent factor loadings, and show no statistical evidence of generating anomaly alphas.

The key to isolating a successful factor model is incorporating information from stock characteristics into the estimation of factor loadings. We propose a model in which risk loadings are partially dependent on observable asset characteristics. We propose a new method, instrumental principal components analysis (IPCA), which treats characteristics as instrumental variables for estimating dynamic loadings. The estimator is as easy to work with as standard PCA while allowing the researcher to bring information beyond just returns into estimation of latent factors and betas. We introduce a set of statistical asset pricing tests that offer a new research protocol for evaluating hypotheses about patterns in asset returns. When a research encounters a new anomaly characteristic, they should test in a multivariate setting against the large body of previously studied characteristics via IPCA. In doing so, the researcher can draw inferences regarding the incremental explanatory power of the proposed characteristic after controlling for the extant gamut. And if the characteristic does contribute significantly to the return model, the research can then test whether it contributes as a risk factor loading or as an anomaly alpha. Thus, the researcher need no longer asks the narrow question, “Is my proposed characteristic/return association explained by a specific set of pre-specified factors,” and instead can ask “Does there exist *any* set of factors that explains the observed characteristic/return pattern?”

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# Internet Appendix

## A Bootstrap Test Monte Carlo

This appendix investigates the finite sample behavior of our test for the null hypothesis  $H_0 : \Gamma_\alpha = \mathbf{0}$ . Our analysis focuses on assessing the size of the test (rejection rates under the null) and power of the test (rejection rates under the alternative).

We simulate data according to the following general model:

$$r_t = Z_{t-1}\Gamma_\alpha\kappa + (Z_{t-1}\Gamma_\beta + \nu_t)F_t + \eta_t.$$

We assume use cross sections of  $N = 500, 5000$ , or  $25000$  assets with  $T = 100$  or  $1000$  monthly observations. We allow for  $K = 3$  or  $5$  factors, and consider sets of  $L = 10$  or  $20$  instruments.

We draw  $\Gamma_\beta$  as a random orthonormal matrix. To do this, we draw an  $L \times K$  matrix of normals,  $M$ , and set  $\Gamma_\beta = MM_C^{-1}$  for  $M_C$  the Cholesky of  $M'M$ . We draw  $Z_t$  as an  $N \times L$  matrix of standard normals. We allow betas to possess a purely unobservable component,  $\nu_t$ , which is an  $N \times K$  array of normals, with the variance parameter chosen such that 50% of the variation of  $\beta_{t-1} \equiv Z_{t-1}\Gamma_\beta + \nu_t$  is due to  $\nu_t$ .

Idiosyncratic returns,  $\eta_t$ , are drawn as a  $N \times 1$  array of normals with time-varying volatility. In particular, the conditional variance  $\eta_t$  is log-normally distributed with its own variance chosen such that on average 15% of return variance is systematic and 85% is idiosyncratic. By incorporating heteroskedasticity akin to that in the data, we can assess the usefulness of the wild bootstrap in conducting inference.

$\Gamma_\alpha$  is a random normal vector that is orthogonal to  $\Gamma_\beta$ . In particular, we draw a  $L \times 1$  vector of normals,  $Y$ , and set  $\Gamma_\alpha = (I_L - \Gamma_\beta(\Gamma_\beta'\Gamma_\beta)^{-1}\Gamma_\beta')Y\kappa$ . Factor realizations  $f_t$  are drawn as a  $K \times 1$  vector of normals.

The distance-from-null is controlled by  $\kappa$ . When  $\kappa = 0$  the model embodies the null hypothesis that  $\Gamma_\alpha = 0$ . For  $\kappa > 0$ , data is generated under the alternative. We consider three values of  $\kappa > 0$  such that when  $\kappa = \kappa_x$ ,  $Z_{t-1}\Gamma_\alpha\kappa_x$  drives about  $x \times 0.25\%$  of the variation in returns.

In every simulated data set, we calculate the  $W_\alpha$  statistic and perform the bootstrap procedure of Section 4.1 to arrive at a  $p$ -value. We also consider a variation on our test that uses

**Table A.1**  
**Size and Power of  $\Gamma_\alpha = 0$  Test**

**Note.** Simulated rejection probabilities of a 5%-level test. Rejection rates in the  $\kappa = 0$  column describe the size of the test. Rejection rates in the  $\kappa = \kappa_1, \kappa_2$ , and  $\kappa_3$  columns describe the power of the test.

$N$	$T$	$K$	$L$	Wild				Non-wild			
				0	$\kappa_1$	$\kappa_2$	$\kappa_3$	0	$\kappa_1$	$\kappa_2$	$\kappa_3$
500	100	3	10	3.4	5.4	32.0	75.0	4.4	5.4	11.3	70.0
500	100	5	20	5.6	6.6	30.2	81.4	5.0	4.4	7.4	68.4
5000	100	3	10	4.6	6.2	27.6	93.4	4.0	5.8	6.6	93.4
5000	100	5	20	4.2	5.2	15.8	82.4	3.2	2.8	5.8	86.8
5000	1000	3	10	4.2	18.0	24.8	75.0	4.6	11.2	21.0	71.8
5000	1000	5	20	3.4	19.8	50.6	90.4	3.4	15.0	32.6	87.8
25000	100	3	10	2.6	7.2	16.0	44.8	2.2	5.6	14.8	38.0
25000	100	5	20	3.6	7.4	15.6	98.6	2.2	6.8	14.6	44.2
25000	1000	3	10	4.4	66.2	78.4	95.8	3.0	54.6	80.6	99.2
25000	1000	5	20	5.0	77.0	93.2	99.8	4.6	76.4	95.2	100.0
Average				4.1	21.9	38.4	83.7	3.7	18.8	29.0	76.0

a standard rather than wild bootstrap. We conduct 1000 simulations with 500 bootstraps for each simulation. Table A.1 reports the results.

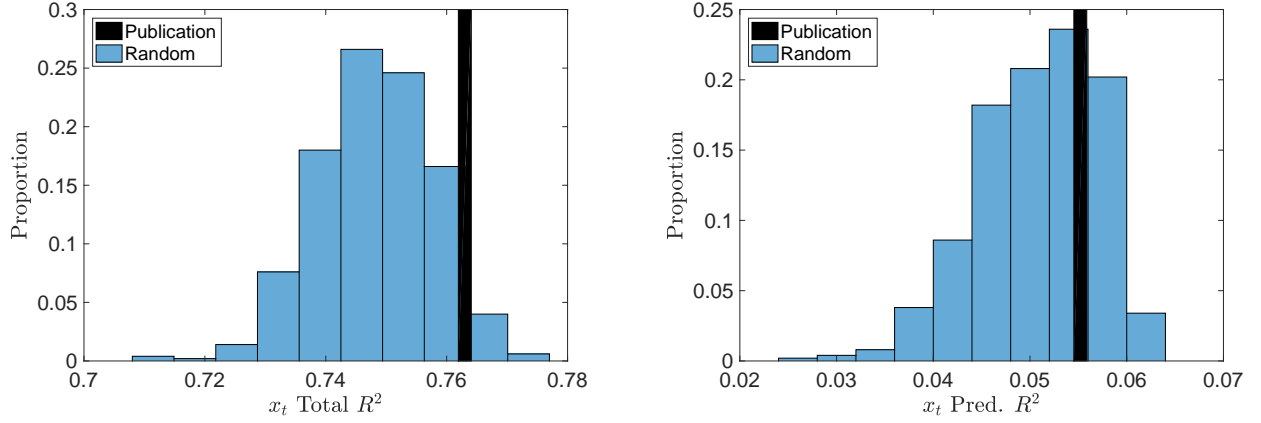
In all cases, the test maintains reasonable size when data are generated under the null. Rejection rates based on a 5% significance level never fall below 2.2% or rise above 5.6%. The power of the test to reject the null when data are generated under the alternative also behaves well. Rejection rates increase steadily with  $\kappa$  and with sample size. Finally, we find that the wild bootstrap indeed improves inference, both in terms of size and power, compared to the standard bootstrap.

## B Characteristic Ordering

Our main analysis orders characteristics according to publication data. In this appendix we investigate the robustness of model fits to alternative orderings. We consider 500 random permutations of the characteristic ordering, and for each permutation estimate IPCA with  $K = 4$ . We report the histogram of total  $R^2$ s and predictive  $R^2$  among characteristic-

Figure A.1: Histograms of  $R^2$  Across Characteristic Orderings

**Note.** Total and predicted  $R^2$  among characteristic-managed portfolios ( $x_t$ ) in 500 random permutations of the characteristic ordering. The results from publication ordering in our main analysis are shown as a black bar.



managed portfolios ( $x_t$ ) in Figure A.1. The results indicate that the total  $R^2$  is very stable across ordering and ranges between 70% and 80%, versus 76.3% in our main analysis. The predictive  $R^2$  ranges from 2.5% to 6.5%, with a modal value almost exactly equal to the 5.5% value in our main analysis.