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Targeting Prospective Customers: Robustness of Machine-Learning Methods to Typical Data Challenges

Duncan Simester, Artem Timoshenko, Spyros I. Zoumpoulis

Abstract. We investigate how firms can use the results of field experiments to optimize the targeting of promotions when prospecting for new customers. We evaluate seven widely used machine-learning methods using a series of two large-scale field experiments. The first field experiment generates a common pool of training data for each of the seven methods. We then validate the seven optimized policies provided by each method together with uniform benchmark policies in a second field experiment. The findings not only compare the performance of the targeting methods, but also demonstrate how well the methods address common data challenges. Our results reveal that when the training data are ideal, model-driven methods perform better than distance-driven methods and classification methods. However, the performance advantage vanishes in the presence of challenges that affect the quality of the training data, including the extent to which the training data captures details of the implementation setting. The challenges we study are covariate shift, concept shift, information loss through aggregation, and imbalanced data. Intuitively, the model-driven methods make better use of the information available in the training data, but the performance of these methods is more sensitive to deterioration in the quality of this information. The classification methods we tested performed relatively poorly. We explain the poor performance of the classification methods in our setting and describe how the performance of these methods could be improved.

Keywords: targeting • machine learning • field experiments • covariate shift • concept shift

1. Introduction
When prospecting for new customers, firms must decide both which customers to target and what promotions to offer them. A standard approach is to run a pilot experiment to measure the response to different promotions. The firm can then use these training data to design a targeting policy that identifies which promotion to send to each prospective customer and then implement the resulting policy on a larger scale. The performance of targeting policies depends upon the choice of the optimization method and the quality of the training data, including the extent to which the training data captures details of the implementation setting. Several practical challenges can arise. We test the robustness of different targeting methods by evaluating their performance when confronted with data challenges that are typical of a prospecting setting.

Our performance comparison uses a sequence of two field experiments. The optimized policies are trained by using data from the first experiment and validated in the second experiment. The criterion we used to select methods was whether a moderately sophisticated retailer would be able to implement the method.

Although many firms have built extensive data warehousing capabilities in recent years, the sophistication of the targeting methods they use varies greatly. Firms such as Amazon and Google have very sophisticated machine-learning capabilities. Other firms outsource their targeting decisions to third-party consultants or data-analysis services. However, many firms rely upon relatively simple targeting models. For example, the retailer that participated in this study has U.S. dollar (USD) revenue in the tens of billions. It has a well-organized and extensive data warehouse, together with a team of data analysts. Before this study, the firm’s data analysts built targeting models using ordinary least squares (OLS). The team did not have experience implementing the machine-learning methods that we evaluate in this paper.

We compare seven machine-learning methods, including two model-driven methods (Lasso and finite mixture models), three distance-driven methods (k-nearest neighbors, kernel regression, and hierarchical...
clustering), and two classification methods (support vector machine (SVM) and chi-square automatic interaction detection (CHAID)). Overall, the model-driven methods perform best. This is particularly true in regions of the parameter space in which the training data provide an accurate representation of the validation data. However, when the quality of the information in the training data deteriorates, the deterioration affects the model-driven methods more, and they perform no better than the other methods.

We evaluate four types of data challenges that affect the quality of the information and the performance of the methods. The machine-learning literature labels the first challenge “covariate shift.” Most methods assume that the distribution of the targeting variables in the training data will be representative of the implementation data, but this is not always the case. For example, if the targeting method is implemented in different geographic regions than the regions in which the training data were gathered, the characteristics of the targeting pool may differ from the implementation pool.

The second data challenge is commonly labeled “concept shift” or “concept drift.” If the underlying response function is different in the training data than in the implementation setting in ways that are not captured by the predictor variables, this will generally result in suboptimal targeting policies. The risk of this is high if the targeting policy is implemented several months after the training data are collected. In the intervening period, changes in the environment through shifts in macroeconomic conditions, competitors’ actions, the firm’s other marketing activities, or just seasonality can all contribute to changes in how customers respond to the firm’s actions.

The remaining two data challenges are particularly relevant when prospecting for new customers. Firms generally have much less information about prospects than about existing customers. For existing customers, they can use past purchasing decisions, but purchasing histories generally do not exist for prospective customers. Instead, firms are generally forced to rely upon demographic measures aggregated at the ZIP code, census block, or carrier route level. We investigate how this aggregation affects the performance of the different methods.

When prospecting for new customers, firms typically trade off a low average response rate with a large long-run expected profit from the new customers that do respond. This leads to what the machine-learning literature refers to as “imbalanced” data with an asymmetric cost of errors. The imbalance in the data results from the very low response rate, whereas the asymmetric cost reflects a much higher cost of false negatives (not mailing to customers who would respond) than false positives (mailing to customers who will not respond). Additionally, the low response rate introduces an imprecise labels problem, as the action that performed best at the finite sample experiment is not necessarily truly optimal. The problem of imprecise labels reinforces the imbalanced-data and asymmetric-cost problems. As we will discuss, these problems are of particular relevance to the classification methods (CHAID and SVM).

Our results reveal an important general finding. Model-driven methods perform better than distance-driven and classification methods when the data are ideal. However, they also deteriorate faster and perform no better than the other methods in the presence of covariate shift, concept shift, and information loss through aggregation. Intuitively, the model-driven methods make the best use of the available information. However, when the quality of the information deteriorates, the performance of these methods is more sensitive to this deterioration. These findings contribute to the debate in the machine-learning literature about which methods are more robust to data challenges. This debate has focused on the impact of covariate shift and concept shift. Our findings indicate that model-driven methods are more sensitive to these data challenges, as well as to loss of precision through aggregation.

These data challenges are extensively studied in the machine-learning literature. Common applications include natural language processing, image analysis, computer vision, robot control, software engineering, bioinformatics, and brain–computer interfacing. For marketing applications, the susceptibility of machine-learning methods to these data challenges is not well understood. Moreover, the empirical investigations of these challenges in the machine-learning literature are almost universally based on simulations. This is one of the few papers to explore the practical importance of these issues using experimental field data.

As with most comparisons of methods, there are important limitations to our findings. We discuss these limitations next.

1.1. Limitations

First, the findings we report are derived from field experiments conducted with a single retailer. It is possible that the findings may not generalize to every marketing setting. In particular, the experiments in our study involved prospecting for new customers. When prospecting for new customers, firms generally have a lot less information than if they are targeting existing customers. With existing customers, firms can often observe each customer’s past purchasing from the firm, which provides a rich source of information for predicting future responses. The performance of the segmentation methods may be very different if they have access to this type of information.
Promotions targeting prospective customers also typically have lower response rates than actions targeted at existing customers. Low response rates affect the distribution of the outcome variable, and this may also affect the performance of targeting methods. In future research, we hope to extend our results to targeting existing customers and to other marketing decisions. Future research may also provide further evidence establishing why some methods perform better than other methods, which is beyond the scope of this paper. Better understanding of the performance differences would also help to improve our understanding of when the results are likely to generalize.

Second, each of the methods that we implemented is representative of a general class of related methods. It is obviously not possible to test every version of every class of methods. Although we chose what we believe to be a commonly implemented version of each class of methods (by moderately sophisticated retailers), we recognize that other versions may perform differently.

Third, in order to target customers with different actions, we need to understand the causal relationship between the actions and the customer outcomes. We study the performance of the models trained using experimental data, which solves the causation problem. We know that differences in outcomes between treatment conditions are caused by the differences in the treatments. In the absence of experimental data, firms and researchers are forced to use other approaches to establish causality, such as natural experiments or reliance on structural models. We caution that our findings do not speak to the performance of these alternative approaches or their robustness to common data challenges. In particular, when applying models to settings with covariate shift and concept shift, it is possible that these observed nonstationarities are related to shifts in unobserved covariates, which could contribute to errors.

1.2. Structure of the Paper
The paper proceeds in Section 2, where we review the literature on the four data challenges. In Section 3, we describe the Stage 1 field experiment used to generate the training data and the Stage 2 field experiment used to validate the trained methods. In the Stage 1 experiment, two promotions are sent to randomly selected households. The U.S. Postal Service groups households by carrier route, and because different households in each carrier route received each treatment, the training data provide a measure of the response to each treatment in each carrier route. The targeting variables all vary at the carrier-route level, and so we train the targeting methods at the carrier-route level, and in the Stage 2 experiment, we randomly select which carrier routes will receive each targeting policy. All of the households in a selected carrier route receive the action recommended for that carrier route. In Section 3, we also describe the 12-month expected profit measure used to train the methods and evaluate their performance. Under the direction of the retailer that participated in the study, this measure uses the membership type that households signed up for (if any), together with their initial store spending, to project total profits over a 12-month period.

We present preliminary results in Section 4, including the average profit earned from each of the seven methods, and a discussion of the relationship between the average profit and the different targeting variables. In Section 5, we evaluate the robustness of the methods to the different data challenges. In Section 6, we extend our analyses to include five additional methods that a more sophisticated retailer might use. The paper concludes in Section 7.

2. Literature Review
As the breadth of machine-learning applications has grown, attention has increasingly turned to how robust methods are to different types of data challenges. We investigate the robustness of the seven targeting methods to four data challenges that are typical in the customer-acquisition setting. In this section, we review the existing literature on each of these challenges, beginning with covariate shift.

2.1. Covariate Shift
Most machine-learning methods assume that the underlying distribution of the data used to train the method matches the distribution of the data on which the trained model will be implemented. However, in many situations this assumption does not hold. For example, Bickel and Scheffer (2007) demonstrate that current approaches to collecting training data for spam-email filtering algorithms generate datasets with different distributional properties from both the global distribution of all emails and the distribution of emails received by a given user. Similar examples can be found in other fields, including natural language processing (Sugiyama and Kawanabe 2012), computer vision (Ueki et al. 2010), robot control (Sutton and Barto 1998), software engineering (Turhan 2012), bioinformatics (Baldi and Brunak 2001, Borgwardt et al. 2006), and brain–computer interfacing (Wolpaw et al. 2002, Sugiyama et al. 2007). The formal definition of covariate shift is that the distribution of the predictive variables in the training data, \( P_{\text{train}}(x) \), is different than the distribution in the implementation data: \( P_{\text{train}}(x) \neq P_{\text{impl}}(x) \) (Shimodaira 2000, Yamazaki et al. 2007, Moreno-Torres et al. 2012). This can occur for a variety of reasons. In our setting, the training data are obtained from a randomized field experiment implemented in two geographic regions. However, the implementation data extend
beyond these two regions and include locations that did not participate in the initial experiment. This introduces the possibility (indeed high likelihood) that the characteristics of the implementation data will not match the training data.

Various tests have been proposed for detecting covariate shift. These statistical tests are all designed to detect differences in multivariate distributions. They include the multivariate $t$-test, the generalized Kolmogorov–Smirnov test (Smirnov 1939, Friedman and Rafsky 1979), the nonparametric distance-based tests (Hall and Tajvidi 2002, Biou and Gyorfi 2005), and the maximum-mean-discrepancy-based test (MMD; Gretton et al. 2012). We use the MMD test in this paper. As we will discuss, this test is distribution-free, computationally efficient, and performs strongly across a variety of applications (Gretton et al. 2012; Sejdinovic et al. 2013, Li et al. 2015).

The machine-learning literature recognizes that not all methods are equally susceptible to covariate shift. Moreover, covariate shift can impact performance in different parts of the parameter space differently. Regions of the parameter space in which performance is most likely to deteriorate are regions that are underrepresented in the training data, but overrepresented in the implementation data. Although accuracy in these regions is important for implementation, the methods have relatively little information in the training data to learn from.

We group methods into three categories: classification methods, distance-driven regression methods, and model-driven regression methods. Distance-driven methods make predictions by weighting local observations more heavily than distant observations, whereas the model-driven methods and classification methods considered in our paper learn globally. These differences can affect how the methods perform in regions of the parameter space that are sparsely populated in the training data (Zadrozny 2004). Because they weight the local observations more heavily, the standard errors in the distance-driven methods may increase quickly when there are relatively few local observations. In contrast, the classification and model-driven methods extrapolate from areas with more observations to make predictions about the areas that are sparsely populated. If the models are perfectly specified, this can work well. However, specification errors mean that these predictions can lead to large errors. For example, training a linear model to predict age from income can lead to unrealistically high age predictions at the right tail of the income distribution. For this reason, covariate shift can lead to predicted value explosions in methods that estimate globally (classification and model-driven methods), whereas distance-driven methods may be more robust to this problem.

Chernozhukov et al. (2017) cite predicted value explosions as an explanation for relatively poor out-of-sample predictions using Lasso (a model-driven method). They argue that the out-of-sample prediction errors tend to be larger than other methods because of the linear extrapolation outside the range of the training data. Similarly, Shimodaira (2000) demonstrates that covariate shift coupled with parameter model misspecification lead to inefficient maximum-likelihood estimates.

Hand (2006a) provides evidence that more flexible models outperform simpler methods when the covariate distribution is stable, but demonstrate similar performance when covariates shift. Hand’s argument is that more complex models are more susceptible to overfitting features of the training data that may not be stable in the validation data. Hand (2006b) further argues that identifying aspects of the problem that deviate from the standard supervised classification paradigm may have more substantial impact on performance than using a more complex method. Alaiz-Rodríguez and Japkowicz (2008) revisit Hand’s conclusion. They use simulations set in a medical domain, predicting the prognosis of patients infected with the flu, and compare the robustness of four methods in the face of covariate shift (and also concept shift). The four methods include two simple methods (a simple 1R classifier and a simple neural network with one node in the hidden layer) and two more complex methods (a C4.5 decision tree and a neural network with 10 nodes). They conclude that the performance of more complex prediction methods does not deteriorate faster than the performance of simpler methods in the presence of covariate shift.

Our findings contribute to the debate about which methods are more robust to covariate shift. Our focus is not on the complexity of the methods, which is the focus of Hand (2006a) and Alaiz-Rodríguez and Japkowicz (2008). Instead, we focus on the ability of the methods to make use of the available information. Among the seven methods that we compare, the model-driven methods make the best use of the information available in the training data. For this reason, they perform the best in the absence of covariate shift. In the face of covariate shift, we show that the performance of these methods also deteriorates faster than other methods, so that they perform similarly to distance-driven and classification methods.

The second data challenge we study is concept shift, which also focuses on differences between the training data and the implementation data.

### 2.2. Concept Shift

Our discussion of covariate shift began by recognizing that machine-learning methods assume that the
distribution of the predictive variables in the training data matches the implementation data. The methods also assume that the relationship between the outcome variable, $y$, and the predictor variables is stable. Changes in the response function between the two datasets is commonly referred to as concept shift (it also sometimes called concept drift or functional relation change). More formally, concept shift refers to situations in which the conditional distribution $P(y|x)$ is different in the training and implementation data, whereas the distribution of covariates $P(x)$ remains unchanged (Schlimmer and Granger 1986, Widmer and Kubat 1998, Hand 2006b, Moreno-Torres et al. 2012).

Similar to most targeting settings, our training data are collected in a different time period than our implementation data. The training data were sourced from an initial experiment in spring, and we implemented the targeting policies six months later in fall. This temporal separation between the training data and the implementation data is almost inevitable, although it may be longer or shorter than the six-month interval in our setting. This interval provides opportunities for changes in the environment that may affect the underlying response function. Changes could include seasonality, wearin or wearout of promotions, other actions by the firm, competitors’ actions, or even macroeconomic shifts. In our case, the retailer reported that customers were exposed to a lot more mass-media advertising during the fall implementation period than during the spring training period.

The general problem of concept shift has been recognized as important and addressed in various domains, including financial prediction (Harries and Horn 1995), business cycles prediction (Klinkenberg 2003), clinical studies in medicine (Kukar 2003, Tsymbal et al. 2006), credit card fraud detection (Wang et al. 2003), computer security and detection of anomalous users (Lane and Brodley 1998), monitoring and control in industrial operations (Pechenizkiy et al. 2010), and student learning modeling in education (Castillo et al. 2003). More applications are illustrated by Gama et al. (2014), who also provide a broad review of concept shift handling techniques.

The machine-learning community has worked on concept shift for over 30 years, starting with the first issue of the journal Machine Learning (Schlimmer and Granger 1986). In later years, the machine-learning community produced theoretical results with guarantees for learning under concept shift: Helmbold and Long (1991, 1994), Kuh et al. (1991), and Kuh et al. (1992) all characterize the maximum severity or frequency of concept changes that is tolerable by a learner. Widmer and Kubat (1996) propose a family of algorithms that flexibly react to concept shift in online learning problems. In a special issue of Machine Learning on concept drift, Dietterich et al. (1998) compiled a collection of works that encompass a wide spectrum of theoretical and practical concept shift-related issues (Auer and Warmuth 1998, Harries et al. 1998, Herbster and Warmuth 1998, Movellan and Mineiro 1998, Vicente et al. 1998).

Research on the robustness of machine-learning methods to concept shift is scarce. Perhaps the closest research to this paper is a study by Alaiz-Rodríguez and Japkowicz (2008), who conduct simulations investigating the prognosis of patients infected with the flu. Recall that we cited this paper as an example of research comparing the performance of methods when covariates shift. Alaiz-Rodríguez and Japkowicz (2008) also study the performance of methods in the presence of concept shift. They demonstrate that more complex prediction methods deteriorate to the same extent as simpler methods in the presence of either covariate shift or concept shift. As we noted earlier, our focus is not on the complexity of the methods, which is the focus of Alaiz-Rodríguez and Japkowicz (2008). Instead, we focus on the ability of the methods to make use of the available information. Among the seven methods that we compare, the model-driven methods make the best use of the information available in the training data. For this reason, they perform the best in the absence of concept shift. In the face of concept shift, we show that the performance of these methods also deteriorates faster than other methods, so that they perform no better than distance-driven and classification methods.

The direct-mail promotions used in this study represent a form of advertising. There has been previous work in the marketing literature recognizing that the response to advertising may be dynamic. This research has focused on developing models of these dynamics, and incorporating them into estimates of the response function. Examples are Naik et al. (1998) and Erdem and Keane (1996). Both papers employ parametric models to capture the dynamics of the customer response to advertising and customer brand choice. Naik et al. (1998) propose a dynamic model for brand awareness that incorporates repetition wear-out (i.e., decline in ad effectiveness due to excessive frequency), copy wearout (i.e., decline in ad effectiveness due to passage of time), and ad quality restoration (i.e., enhancement of ad effectiveness following a media hiatus). The model is then used to optimize advertising sequencing. Erdem and Keane (1996) construct structural consumer-behavior models where consumers update their brand choices based on usage experience and advertising exposure. Their structural-estimation strategy requires them to specify explicit behavioral models of consumer choice behavior and then estimate the behavioral-model parameters. Erdem and Keane (1996) argue that the advantage of their
structural models is that the model parameters are invariant to policy changes and that, therefore, their models can be used to evaluate different policies.

In both these papers, as well as in the marketing literature in general, the scope is to model explicitly the customer response and how it changes, pinning down the different factors that drive it. In sharp contrast, the machine-learning community has attempted to describe and analyze concept shift in a model-free way, without losing generality.

In order to incorporate dynamics into the response function, the dynamics must be well understood. In our setting, the change in prospective customer responses to promotions may reflect many different factors. Some of these factors may not be regularly occurring (such as competitors’ actions or changes in macroeconomic conditions), so that the change may not be consistent over time. This makes the concept shift that we study difficult to either predict or model.

2.3. Aggregation of the Targeting Variables

Data aggregation is an important topic in marketing and forecasting research. Because individual-level data are often unavailable or expensive, previous studies have sought to understand the value of individual versus aggregate data and how aggregation affects the performance of a model. In the prospecting problem we study, targeting models are often trained by using aggregate data. Individual purchasing histories are not available because the customers have not previously purchased. In the absence of past purchasing histories, firms are often forced to rely upon demographic data. However, demographic data are expensive to purchase at the household level and are often not accurate. Instead, many firms target prospective customers by purchasing demographic data aggregated to the ZIP code or carrier-route level.

The targeting variables used in this study are all aggregated at the carrier-route level. However, some carrier routes have more households in them than other carrier routes. The degree of aggregation thus varies across carrier routes, and it is this variation that we exploit. In carrier routes with relatively few households, the information is less aggregated and more precise than in larger carrier routes that contain more households.3

The marketing literature contains many examples of papers studying the performance of models at different levels of aggregation. Notably, aggregate-level models often perform as well as models built using disaggregate data. For example, Andrews et al. (2011) compare sales-promotion response predictions with individual-level or store-level data. They find that, in general, the individual-level models, which capture customer heterogeneity, do not produce more accurate sales response predictions. Gupta et al. (1996) also compare models built using household versus store-level data. They reach a similar conclusion that disaggregate models may not improve performance.

However, not all results favor aggregate models. Foekens et al. (1994) estimate alternative models at the store-level, chain-level, and market-level model. They compare the models both on whether the parameters are reasonable and on how accurate the sales forecasts are. In general, the less-aggregate models performed better than the market-level model on both benchmarks. More recently, Abhishek et al. (2015) compare models built using daily sponsored search data versus disaggregate data that include intraday variation in ad position. They show that the aggregate (day-level) data yield biased estimates. In an example from economics, Pesaran et al. (1989) compare aggregate (groups of industries) and disaggregate (industry-level) models for predicting the demand for labor. The disaggregate models predict more accurately.

There is also an older literature that characterizes when summing forecasts from less-aggregate models is expected to perform better than using a single-aggregate model. Grunfeld and Griliches (1960) and Edwards and Orcutt (1969) conclude that the superiority of the less-aggregate models depends upon the quality of the model specification. Aigner and Goldfeld (1973, 1974) show analytically why this is true and provide more general conditions under which less-aggregate models will perform better. The conditions favoring less-aggregate models include uncorrelated errors (across subsamples) and negative correlations in the predictor variables (across subsamples). On the other hand, if there is substantial measurement error in the predictor variables, this favors the performance of the aggregate models. Aggregate models will also tend to have lower errors when the errors across the subsamples are negatively correlated or the predictors are positively correlated. After reviewing these characteristics, Foekens et al. (1994) conclude that, in practice, the relative performance of aggregate and disaggregate models is difficult to anticipate and may vary across settings. This explains why the comparison of aggregate and disaggregate models continues to be an important research topic. In our setting, where we target prospective customers using aggregate demographic data, it is unclear whether the loss of information due to greater aggregation will outweigh the possible cancellation of disaggregate measurement error.

The machine-learning literature addresses the issue of aggregation through the lens of information loss. The performance of predictive models deteriorates with lower-quality predictors, but the rate of deterioration varies between methods. Model-driven methods can adjust to the weak predictors by assigning smaller weights to these predictors. For
example, Lasso assigns a zero weight on the subset of variables with low prediction power (Tibshirani 1996, Friedman et al. 2001). On the other hand, distance-driven methods may be more sensitive as weak predictors introduce noise to the standard definitions of distance, such as Euclidean distance (Yang and Jin 2006, Xiang et al. 2008, Bellet et al. 2013). Distance-driven methods also suffer from the curse of dimensionality, which can be exacerbated by the inclusion of weak predictors (Jain and Zongker 1997, Indyk and Motwani 1998).

We compare how much the performance of the different methods changed when data were more aggregated. We found that the performance of model-driven methods deteriorates more quickly than distance-driven methods. However, this is not because the model-driven methods perform worse than other methods with more aggregate data; all of the methods perform similarly. Instead, the model-driven methods perform a lot better than distance-driven methods when the data are less aggregated, and they deteriorate faster as the level of aggregation increases. Intuitively, the model-driven methods appear to make the best use of the more precise information in the targeting variables in the less aggregate data, and this performance is most susceptible to erosion in the quality of that information.

However, beyond interpreting aggregation as a measure of loss of information in the targeting variables, we also see evidence of a positive effect of aggregation. SVM performs better in larger carrier routes than in smaller carrier routes. The evidence that the performance of SVM improves with aggregation reflects the sensitivity of this method to the imprecise labels problem in smaller carrier routes.

2.4. Imbalanced Data and Asymmetric Costs for Classifiers

The fourth data challenge that we study is the role of imbalanced data and asymmetric costs. This data challenge is particularly relevant to the performance of the classification methods (CHAID and SVM). In Section 5.4, we will present an example that illustrates why classification methods can perform poorly when data are imbalanced and the cost of errors is asymmetric. There is an extensive machine-learning literature on this topic, but we defer a discussion of this literature to Section 5.4. The discussion will be easier to interpret when presented alongside the illustrative example.

We complete our review of the literature by discussing other comparisons of machine-learning methods.

2.5. Other Comparisons of Methods

Comparisons of methods have been conducted in various domains independently of the four data challenges we identify. We start with marketing and, in particular, customer segmentation. Similar to our setting, McCarty and Hastak (2007) compare segmentation methods for direct marketing. They report that CHAID outperforms basic recency, frequency, and monetary value (RFM) analysis in settings where the response rate is low and the marketer can target only a small portion of the entire database. We note that their RFM analysis uses transaction variables about the past behavior of customers that are not available in prospecting campaigns. Olson et al. (2009) find that data-mining methods (logistic regression, decision trees, and neural networks) performed better than basic RFM analysis for customer segmentation, but found little variation in the performance of the data-mining methods.

In economics, Stock and Watson (2005) empirically compare methods for macroeconomic forecasting and find that models that reduce dimensionality by using factor analysis are more accurate than models that do not, such as OLS regression and bagging. In microfinance, Wu et al. (2010) find that naive Bayes and Bayesian networks perform better than clustering methods when making decisions about giving loans to subprime borrowers.

Finally, there is a rich literature in comparing methods for medical predictions, yet no overarching statement can be made about the relative performance of families of methods. We provide some characteristic examples. Tong et al. (2016) report that Lasso logistic regression predicted all-cause non-elective readmission risk of patients better than stepwise logistic regression, AdaBoost, and a readmission risk index (especially when the sample size is small). A decision tree (C5) outperformed a neural network and logistic regression in predicting breast cancer survivability in a study by Delen et al. (2005). SVM outperformed logistic regression, discriminant analysis, neural networks, fuzzy clustering, and random forests in predicting diabetes in a study by Tapak et al. (2013). Penny and Chesney (2006) find that neural nets outperformed CART, logistic regression, and another tree-based classification algorithm (C5) for predicting death following injury.

In the next section, we introduce the research context, describe the design of the experiments, and discuss the targeting variables and the output measure used to train and evaluate the models.

3. Data Overview

3.1. Research Context

Data for this study were provided by a large retailer that operates a large number of stores in the United States. The retailer sells a broad range of products including perishables, sundries, and durables. Customers can only
purchase if they have signed up for a membership. The retailer regularly mails promotions to prospective members in order to increase its membership base. We study two types of promotional offers. The first offer is a $25 paid 12-month membership, which represents a 50% discount off the full price. The second offer is a 120-day free trial. Customers who want to maintain their memberships after the trial period must purchase a regular membership at the full price. When new customers register for a membership, they provide their name and mailing address. This is used to identify which households responded to which direct-mail promotions.

3.2. Design of the Stage 1 Experiment
The first-stage (training) experiment included 1,185,141 households in a mailing list purchased from a third-party commercial data supplier. The households were all located in two geographic regions. The households were assigned to three experimental conditions, randomized at the household level. The three conditions included a control group that received no promotion offer, a group that received the $25 paid offer, and a group that received the 120-day free trial. The promotions were highlighted on the front cover and inside the front cover and back cover of a 48-page book of product-specific coupons. The treatments were repeated twice approximately six weeks apart, so customers received the same offer twice. The first treatment was implemented in early February 2015, and it was then repeated in late March.

The U.S. Postal Service organizes households into carrier routes. These routes identify the households that each letter carrier visits. There are typically 200–400 households per carrier route, and they all fall within the same ZIP code. Both when training the models using the Stage 1 field experiment and when implementing the targeting policies in Stage 2, we used data aggregated to the carrier-route level.

The Stage 1 experiment included 5,976 carrier routes. Because we randomized at the household level in this stage, each carrier route includes households randomly assigned to each of the three experimental treatments. Therefore, for each carrier route, we can calculate the profit earned under each of the experimental treatments: $25 paid offer, 120-day free trial, and control.

3.3. Targeting Variables
The Stage 1 experiment was used to provide data for training the seven targeting models. Before training the models, we needed to decide which targeting variables to use. Recall that our goal is to compare typical implementations of each method (by a moderately sophisticated retailer) and to evaluate how robust their performance is to different data challenges. This goal of implementing a version of the model that a moderately sophisticated retailer would implement is a different goal than identifying the variant of each method that yields the optimal performance. For this reason, we chose to use the same variables that the firm used in its OLS-based training models. Moreover, like the retailer, we restricted attention to linear relationships and did not include any interactions between the variables or nonlinear transformations of the variables. In Section 6, we investigate whether including pairwise interactions between the targeting variables improves performance.

The retailer provided 13 targeting variables for the carrier routes in Stage 1 and then subsequently provided the same targeting variables for the carrier routes in Stage 2. All variables vary at the carrier-route level. Five of the variables—Age, Home Value, Income, Single Family, and Multifamily variables—were purchased by the retailer from a third-party commercial data supplier. The remaining variables were constructed by the retailer using the retailer’s own data. A complete list of variables, together with their summary statistics and definitions, is presented in Table 1.

In preliminary analysis, we also investigated estimating the models at the household level instead of the carrier-route level. To facilitate this comparison, the retailer purchased household-level data for the Age, Home Value, and Income variables from the third-party

| Table 1. Summary Statistics of Targeting Variables |
|-----------------------------------------------|
| Variable          | Stage 1       | Stage 2       |
| Age              | 56.2955 (0.0734) | 56.9604 (0.0595) |
| Home Value (in 1,000s) | 159.9438 (1.1511) | 261.0733 (1.8301) |
| Income (in 1,000s)  | 64.6944 (0.4100) | 87.9428 (0.6605) |
| Single Family     | 0.7718 (0.0036) | 0.7792 (0.0029) |
| Multifamily       | 0.1738 (0.0028) | 0.2172 (0.0029) |
| Distance          | 10.6970 (0.1075) | 9.6439 (0.0815) |
| Comp. Distance    | 9.3034 (0.1000) | 10.8095 (0.1145) |
| Penetration Rate  | 0.2372 (0.0226) | 0.6395 (0.0398) |
| 3yr Response      | 11.4717 (0.1016) | 13.9854 (0.0965) |
| F flag            | 0.5651 (0.0064) | 0.5367 (0.0049) |
| M flag            | 0.2917 (0.0059) | 0.3079 (0.0045) |
| Past paid         | 0.0303 (0.0004) | 0.0417 (0.0003) |
| Trials            | 0.0021 (0.0001) | 0.0037 (0.0001) |

Notes. The table reports summary statistics for the 13 targeting variables in Stage 1 and Stage 2. Standard errors are in parentheses. The unit of analysis is a carrier route, and the sample size for all 13 variables is 5,976 in Stage 1 and 10,419 in Stage 2. Age is the age of head of household. Home Value is estimated home value. Income is estimated household income. Single (Multi) Family is a binary flag indicating whether the home is a single (multi) family home. Distance (Comp. Distance) is the distance to nearest store for this retailer (competitors’ store). Penetration Rate is the percentage of households in the ZIP code that are members. 3yr Response is the average response rate to mailings to this ZIP code over the last three years. F (M) Flag is a binary flag indicating whether the retailer considers the ZIP code “far” (a “medium” distance) from its closest store. Past Paid is the proportion of households in the ZIP code that were previously paid members. Trials is the proportion of households in the ZIP code that have been identified as households who repeatedly sign up for trial memberships.
commercial data supplier. We used a holdout sample and the outcomes from the Stage 1 experiment to compare whether training the models at the household level improved performance over models trained at the carrier route level. There were no improvements in the ability to predict outcomes in the holdout sample when using household-level data. One possible explanation is that the household-level data provided by the data provider are not sufficiently accurate to improve performance. The household-level data are more expensive to purchase, and so throughout the study, we use data aggregated to the carrier-route level.

3.4. The Targeting Methods

The Stage 1 experiment provided an outcome measure for each of the three treatments for all 5,976 carrier routes that participated in that experiment (we describe the outcome measure in detail later in this section). This outcome measure together with the 13 targeting variables comprise the data that we use to train the seven targeting models.

The targeting methods that we compare use two different approaches to design optimal targeting policies. Most of the methods use a regression-based approach, under which a separate model is trained for each of the three treatments (no mail, $25 paid promotion, and the 120-day trial promotion). These models are then used to predict the outcomes for a new observation (i.e., a new carrier route). The methods assign to the new observation the treatment with the highest predicted profit. Regression-based methods can be further categorized as nonparametric distance-driven methods or parametric model-driven methods. We implement three distance-driven methods together with two model-driven methods (see below).

An alternative approach to the problem is to classify the observations in the training data according to which of the treatments yielded the highest profit. The 13 targeting variables are then used to predict this classification of the training data outcomes. We evaluate two classification methods.

Distance-driven methods
- Kernel regression
- k-nearest neighbors (k-NN)
- Hierarchical clustering (HC)

Model-driven methods
- Lasso regression
- Finite mixture models (FMM)

Classification methods
- Chi-square automatic interaction detection (CHAID)
- Support vector machines (SVM)

We also evaluate three naïve benchmarks. These benchmarks implement “uniform” policies, which assign each new observation the same treatment: the policy assigning the $25 paid membership uniformly, the policy assigning the 120-day free trial uniformly, and the policy assigning the no-mail treatment uniformly.

Recall that our criterion for selecting these methods was whether a moderately sophisticated retailer would be able to implement the method. We used the same criterion when formulating each of the methods. Because the implementations are not novel (by design), we relegate a discussion of each method and its implementation to the online appendix.

3.5. Design of the Stage 2 Experiment

The second-stage (validation) experiment involved 4,119,244 households organized into 10,419 carrier routes. The mailing list for this experiment was purchased from the same third-party data supplier that provided the mailing list for the Stage 1 experiment. The 10,419 carrier routes were randomized into 10 experimental conditions. These included the seven optimized conditions (one for each of the seven segmentation methods) and three uniform conditions ($25 paid offer, 120-day free trial, and no mailing).

In Stage 2, we randomized by carrier route instead of households, so that every household in a carrier route was in the same experimental condition. This decision was motivated by lower mailing costs. The U.S. Postal Service offers cheaper mailing rates if every household in a carrier route receives the same mailing. Notice that this is a difference from the Stage 1 experiment, where randomization occurred at the household level, thus ensuring a measure of the response to each of the three treatments ($25 paid offer, 120-day free trial, and control) in each carrier route in Stage 1.

The Stage 2 experiment shared many of the same features as the Stage 1 experiment. The study involved the same retailer sending direct-mail solicitations to prospective customers identified through rented mailing lists. As in the Stage 1 experiment, the mailing treatments in the Stage 2 experiment were repeated six weeks apart, with customers receiving the same treatment in each wave. The promotions were also the same, including a $25 discounted membership, a 120-day free trial, and a no-mail (control) condition. We used the same 13 targeting variables that were available in the first-stage experiment (summary statistics for the Stage 2 mailing list are also provided in Table 1).

However, there are several differences in the design of Stages 1 and 2. First, the households were in a much broader geographic area in Stage 2, with just 2% of the households located in the same geographic area as the Stage 1 experiment. Second, the Stage 2 experiment was conducted in the fall (starting on August 23, 2015), whereas the Stage 1 experiment was conducted in the spring (of the same year). Third, the Stage 1 treatments were randomly assigned at the household level, whereas in Stage 2 the 10 mailing policies were...
randomly assigned at the carrier-route level. Fourth, in Stage 2, the promotions were mailed to prospective customers using a postcard, which was printed on both sides and highlighted the offer on each side. Recall that in Stage 1, the offers were printed on the outside and inside covers of a 48-page book of coupons. Finally, the Stage 2 experiment coincided with a mass media advertising campaign by the retailer. There was no such mass media advertising during the Stage 1 experiment.

These types of differences between the experiments are typical in a field setting. They are likely to lead to differences in the response functions between the training and validation experiments, which will tend to diminish the accuracy of the optimized policies. However, the randomization ensures that this affects all of the optimization methods. Moreover, this variation provides an opportunity to compare the methods in realistic conditions. In practice, these types of differences are common, and a comparison of the methods across identical experiments is perhaps less informative than a comparison of the methods in realistic conditions. We will exploit these differences in Section 5, where we evaluate how robust the different methods are to differences in the training and validation data.

3.6. Profit Measure

We train the methods and compare their performance using the “profit” earned from each household. This profit measure estimates profits in the 12 months after each experiment’s first mailing date. Recall that the two experiments are only 6 months apart, and so it was not possible to measure the full 12-month outcome from the first experiment before the start of the second experiment. Instead, the retailer provided a formula for projecting 12-month profits using an initial “tracking window.”

Mailing decisions for the Stage 2 experiment needed to be made several weeks before the mail date of that experiment. In order to make these mailing decisions, many steps were required to construct the Stage 1 training data, train the models, and finalize the experimental design for Stage 2. These steps all had to be performed after the end of the tracking window for the Stage 1 experiment. As a result, we had to extract the Stage 1 data and start preparing for the second experiment well before the mailing date of the second experiment. Consequently, the training data are constructed by using a tracking window from the Stage 1 experiment that includes 63 days after the first mailing date to identify new members and 77 days after the first mailing date to track transactions from these new members. To ensure that we validated the seven methods using the same measure on which we trained them, we used an identical tracking window and estimation formula to compare their performance in the Stage 2 experiment. The retailer’s profit estimation incorporates key factors that contribute to customer retention and profitability. First, it recognizes that membership revenue has no cost of goods sold and contributes directly to profit. Second, it applies a constant profit margin to in-store purchases (which is consistent with the retailer’s pricing practices). Third, it distinguishes between households that did not respond, households that signed up for a trial membership, and households that signed up for a regular paid membership. The distinction between trial and regular membership is important. The retailer only receives membership revenue from the paid memberships. Moreover, because not all trial members convert to regular memberships at the end of their trial, the membership type plays an important role in customer retention over the 12 months. This conversion probability has been carefully studied by the retailer and is incorporated into the profit calculation. Finally, the projection of in-store purchasing over the 12 months was specific to each household and is based on the household’s in-store spending during the first 77 days.

Although the profit calculation is confidential, we document the sources of variation in the online appendix. The mailing costs only varied according to whether a household received a promotional mailing. Because this variation is small, it explains little variation in the 12-month expected profit measure. Instead, the variation in expected profit is almost equally attributable to a household’s membership decisions (including the choice of membership type) and the amount that new members spent in the store during the first 77 days.

In the online appendix, we also discuss the possibility that a retailer may impose a ceiling on the total number of mailings. We discuss how this type of constraint could be accommodated by the model-driven and distance-driven methods. For ease of exposition, throughout the paper, we use the term Profit to refer to the expected 12-month profit measure described in this subsection.

4. Preliminary Results

4.1. Average Profit in Each Experimental Condition

We compare the Profit earned from the households in each of the experimental conditions in Figure 1. The findings reveal that the policy produced by Lasso yielded the highest average profit. The average profit was significantly higher than CHAID and SVM, and it also significantly outperformed all uniform policies (p < 0.05). The k-NN method also significantly outperformed CHAID (p < 0.01). However, it did not significantly outperform the uniform $25 condition.
We can also compare the performance of the methods when grouping the methods using our taxonomy of methods. In Figure 2, we report the analysis when pooling the households according to this taxonomy. Notice that this grouping preserves the benefits of randomization, although the sample sizes vary because there are more distance-driven methods than model-driven or classification methods. The results clearly favor the distance- and model-driven methods over the classification methods. The two classification methods (CHAID and SVM) are the two worst-performing methods. Indeed, when we pool the outcomes by method type, the distance- and model-driven methods yield policies that are both significantly better than the classification outcomes ($p < 0.01$). The difference between the distance- and model-driven methods is not significant.

4.2. Comparison with the Uniform $25 Policy

Although the Lasso method significantly outperforms the uniform policy of sending every household the $25 paid offer, it is the only optimization method to do so. Although most of the other optimized policies earn higher average profits than the uniform policies, the differences compared with the uniform $25 paid policy are generally not statistically significant. Although this may seem disappointing, it is not surprising. Most of the methods choose to send the $25 paid offer to the majority of households. For households for which a policy would recommend sending the $25 paid offer, there is obviously no difference in the expected profit compared with the uniform $25 policy. If we want to focus on the differences between an optimized policy and this uniform policy, we need to focus on the households for which the policies are different. In particular, we need to compare the households for which the optimized policy would not send the $25 paid offer. Because of the experimental variation, we can make this comparison using a randomly selected group of customers who received the $25 paid offer (those assigned to the uniform policy) and a randomly selected group of customers that received another treatment (those assigned to the optimized policy).

We can illustrate this logic more clearly using an example. Consider the households in the Lasso condition and the households in the uniform $25 paid condition. We can ask what action Lasso would have recommended for all approximately 800,000 customers (pooled across both conditions). It would have recommended sending the $25 paid offer to 73.63% of them, sending the 120-day free trial to 8.00% of them, and not mailing to the remaining 18.37%. These three subgroups of households are systematically different (otherwise, Lasso would not have chosen to treat them differently). However, within each subgroup, there is a sample of customers randomly assigned to the Lasso policy and an equivalent sample randomly assigned to the uniform $25 paid policy. We can safely compare these equivalent samples. The results are summarized in Figure 3. Where Lasso chose the 120-day or no-mail treatments over the $25 paid treatment, it outperformed the uniform $25 policy. The difference is statistically significant ($p < 0.01$) for the no-mail treatment, and when pooling the 120-day and no-mail groups (the columns at the far right in Figure 3).

Reassuringly, we do not observe a significant difference between conditions for the households for which Lasso recommended sending the $25 paid offer. This is true even though this is the largest subgroup of...
households (73.63% of them). For these households, the comparison between conditions represents a randomization check. They received the same treatments and so any differences in the outcome could only be attributed to differences in the households themselves. The findings also reveal another distinctive pattern. Lasso recommends mailing the $25 paid offer to the most valuable households. It is only the less valuable households to which it chooses to send the 120-day free trial (or not to mail). Further investigation also reveals that the customers to whom Lasso would have recommended not mailing are in carrier routes located a long way from the retailer’s stores and that have had historically very low response and membership rates. Lasso chooses not to mail to these customers because mailing is costly and these customers are unlikely to respond, even if they receive a promotional mailing. This analysis is described in the online appendix, where we also repeat the analysis in Figure 3 for all of the optimized models.

As a final set of preliminary results, in the next subsection, we report how the profits earned from the three experimental treatments in Stage 1 varied with respect to each of the targeting variables.

4.3. Profit and the Targeting Variables

To demonstrate the relationship between the Profit and the targeting variables, in the online appendix, we report the parameter estimates when using OLS to regress the Profit outcome measure on the 13 targeting variables. There are no significant differences in the direction of the relationship between profits and the targeting variables across the three treatment conditions, but coefficients vary in their magnitudes. This variation provides an opportunity for the targeting methods to vary the optimal action across carrier routes. Across the three models, the strongest indicator that a carrier route will yield large profits is a high previous response rate (3yr Response). The coefficient on this variable is approximately three times larger than any other coefficient (in absolute value). Other significant coefficients indicating larger expected profits include: a short distance to the nearest own store (Distance), a long distance to the competitors’ store (Comp. Distance), a concentration of single-family housing (Single Family), a low average age (Age), and a high proportion of households that were previously paid members (Past Paids).

Our initial findings indicate that the model-driven and distance-driven methods had a better overall performance than the classification methods. In the next section, we investigate the robustness of this finding by reexamining the performance of the methods in different regions of the parameter space. This allows us to evaluate the relative performance of the methods when confronted with data challenges that are typical in a prospecting setting.

5. How Well Do the Methods Address the Challenges of Targeting Prospects?

In the introduction, we identified typical challenges of using the response from an initial experiment to target prospective customers. The first challenge is the risk of covariate shift. If the distribution of the targeting variables in the Stage 1 training data are different than the Stage 2 validation data, then the trained policies may not extrapolate well to the validation data.

The second challenge is that the response function itself may not be stationary, which the machine-learning literature refers to as “concept shift.” This could reflect a wide variety of factors, including seasonality, macroeconomic conditions, competitive actions, or exposure to intervening promotions. If the response function changes from the training data to the validation data, this may contribute to deterioration in the performance of the optimized policies.

A third obstacle is that the targeting variables are often measured at an aggregate level. This is particularly common when targeting prospective customers. Because these customers have not previously purchased, there is no past purchasing data to use as a targeting variable. Instead, firms often rely upon demographic
variables, which are typically aggregated across census blocks, ZIP codes, or carrier routes.

We start this section by evaluating the seven targeting methods on different segments of the data to assess how well the methods address these first three challenges. We conclude the section by focusing on the fourth data challenge to explain why the classification methods performed so poorly. This discussion focuses on data imbalance and asymmetric costs of error. Prospecting for new customers typically yields a very low response rate, but a large profit from the prospective customers that do respond. The machine-learning literature recognizes that these characteristics can cause difficulties for classification methods. We discuss how the methods can be modified to overcome these difficulties and improve performance. We start by investigating the challenge posed by covariate shift.

5.1. Covariate Shift

One factor that could influence the performance of targeting models is the extent to which the distribution of the customers’ characteristics in the Stage 2 validation data matches the distribution in the Stage 1 training sample. We would expect targeting models to perform better (compared with naïve benchmarks) in regions of the parameter space that are well represented in the training data.

This issue is particularly relevant in settings such as ours, where the geographic regions in the training data and validation data vary. Recall that in our study, the training data are drawn from just two geographic regions, whereas the validation data are drawn from a much broader geographic area. As a result, it should not be surprising if the validation data contain regions of the parameter space that are not well represented in the training data.

We first employ a statistical test to establish the covariate shift between our spring training data and fall validation data. We formally identify the covariate shift between training and validation data using the maximum mean discrepancy test (MMD). The MMD test is a statistical test of the null hypothesis that two distributions, \( f \) and \( g \), are equal, \( H_0: f = g \), against the alternative hypothesis \( H_1: f \neq g \). Suppose there are \( n \) samples drawn from the multivariate distribution \( f \), and \( m \) samples drawn from the distribution \( g \). The test first finds a smooth function that is large on the points drawn from \( f \), and small (negative) on the points drawn from \( g \). The test statistic, MMD, is then the difference between the mean function values on the two samples. When the MMD is large, the samples are likely drawn from different distributions.

The choice of the class of smooth functions is important for the performance of the test statistic. There is a trade-off between the richness of the class of functions and the convergence properties of the estimator. We want MMD to vanish only when \( f = g \), but the empirical estimate of MMD converges to its expectation slowly for richer classes. Gretton et al. (2012) derive the test thresholds for the MMD statistic with functions from a reproducing kernel Hilbert space. In our test, we use the Gaussian kernel with a bandwidth equal to the median Euclidean distance between the data points (Caputo et al. 2002). For computational efficiency, we reduce the sample size by applying the MMD test to 5,000 carrier routes randomly drawn from each of the training and validation datasets. The test rejects the null hypothesis of equal distributions at the 1% significance level.

As an initial investigation of the effect of covariate shift on the performance of the methods, we first calculated the mean and standard deviation of each of the 13 targeting variables using the Stage 1 training data. We then identified carrier routes in the Stage 2 validation data for which one or more of the variables was at least two standard deviations away from the (training data) mean. This procedure revealed that 60.5% of Stage 2 carrier routes fell outside the two standard deviation range on at least one of the 13 targeting variables. We classified these validation sample carrier routes as “outside the range” of the training data, and the remaining carrier routes as “inside the range.” We then recalculated the average outcome for each method using the two groups of carrier routes. The findings are summarized in Figure 4.

The findings reveal several interesting patterns. First, we see that the households in the Stage 2 validation data that were outside the range of the Stage 1 training data were generally more valuable households. Another way to see this is to compare the characteristics on which Stage 1 and Stage 2 differ (Table 1), with the analysis in the online appendix, where we show which characteristics are associated with higher Profit. Profits tend to be higher in carrier routes with a higher previous response rate (3yr Response); that are closer to the retailer’s stores (Distance) and further from the competitors’ stores (Comp. Distance); that have a higher concentration of single-family housing (Single Family); that are younger in age (Age); and that have a higher proportion of households that were previously paid members (Past Pays). We see in Table 1 that the Stage 2 sample has on average a higher three-year response rate, is closer to the retailer’s stores, further from the competitors’ stores, has about the same concentration of single-family housing and about the same age, and has a higher proportion of households that were previously paid members.

Second, the $25 paid uniform policy outperforms the other uniform policies on the households that are outside the range of the training data, but the 120-day trial is the best uniform policy inside the range of the training data. This result is consistent with our
observation in Section 4.2 that Lasso’s optimized policy recommends mailing the $25 paid offer to the most valuable households, and the 120-day free trial to the less valuable households.

Third, when we focus on the households that were inside the range of the training data, the power of the model-driven methods is revealed. Lasso and FMM sharply outperform the other methods and also all three of the uniform policies. The implication is that these methods make the best use of the information in the training data.

Finally, the seven optimized methods all perform similarly on the households outside the range of the training data. Moreover, all seven methods yield optimized policies that underperform the $25 paid uniform policy. This highlights the cost of covariate shift. Training models on data that are not representative of the data that the models will be implemented on yields relatively poor policies compared with the naïve benchmark of mailing the $25 paid promotion to everyone.

We highlight how covariate shift contributes to the deterioration in the performance of the methods by comparing their performance to a naïve benchmark. For the naïve benchmark, we use the most profitable uniform policy. Inside the range of the training data, the most profitable uniform policy was the 120-day trial, whereas outside the range of the training data, the $25 paid promotion was the most profitable. In Figure 5, we compare the methods grouped using our taxonomy against these two benchmarks.

Inside the range of the training data, the model-driven methods significantly improve upon their benchmark. However, outside the range all methods perform equally poorly compared with that benchmark. The deterioration in performance due to covariate shift is particularly striking for the model-driven methods. The advantage they enjoy within the range of the training data is eliminated.

One interpretation of these findings is that model-driven methods make better use of the information provided by the covariates in the training data. When the validation data matches the training data, this results in improved performance. However, when the training and validation data are poorly matched, exploiting the information in the training data does not help to improve performance in the validation data. Under this interpretation, the deterioration in performance is larger on the methods that make the best use of the training data.

Recall from our discussion in Section 2 that there are conflicting arguments in the machine-learning literature about how robust different types of methods will be in the presence of covariate shift. These arguments focus on the way that the methods predict outcomes in regions of the training data that are sparsely populated. Distance-driven methods make predictions by weighting local observations more heavily than distant observations, whereas the model-driven methods considered in our paper learn globally (Zadrozny 2004). When we examine the predicted profits in the sparsely populated regions of the training data, we see more extreme predictions and larger variance in the predictions from the distance-driven methods than the model-driven methods. This is not consistent with an argument that model-driven methods yield more extreme predictions when they extrapolate from areas with more observations to make predictions about the areas that are sparsely populated. Instead, the large variance in the predictions from the distance-driven methods is consistent with local estimation in sparsely populated regions.

The covariate shift findings in Figures 4 and 5 indicate that when the distance between the training data means and the validation data are too large, then the targeting methods perform worse than a naïve benchmark. We next evaluate whether the targeting methods may also perform worse than a naïve benchmark if the distance is too small. It is possible that the validation data may be different from the

Figure 4. The Average Stage 2 Profit When Grouping the Households According to Whether They Are Inside or Outside the Range of the Training Data

Notes. The profits are indexed to 100 in the No Mail control for the Inside the Range data point. We categorize the households in the Stage 2 validation data as falling inside the range of the Stage 1 training data if they have values on all 13 targeting variables within two standard deviations of the average value in the training data. Complete findings are reported in the online appendix.
training data because the validation data are too few standard deviations from the training data means.

To illustrate this, we group the carrier routes according to the largest deviations from the mean values of the 13 targeting variables in the training-group data. In particular, we use the Stage 1 training data to calculate the mean and standard deviation of each of the 13 targeting variables. For each variable and carrier route, we can then calculate the number of standard deviations between the value of this variable in the carrier route and the training-group mean. We group the carrier routes using the largest absolute deviation across the 13 variables (we label this the \textit{Maximum Deviation}).

In Figure 6, we report a histogram of the \textit{Maximum Deviation} for carrier routes in the training and validation samples.

We see that relatively few of the carrier routes in the validation data have \textit{Maximum Deviations} less than 1.5 standard deviations from the training data means. In contrast, many of these carrier routes have \textit{Maximum Deviations} at least three standard deviations from the training data means.

In Figure 7 we see how this affects the performance of the targeting methods in Stage 2. In particular, we report the average profits within each group of Stage 2 carrier routes, where the profits are indexed at 100 using the most profitable uniform policy (within each group) as a benchmark. The findings indicate where the targeting policies were able to improve upon the naïve benchmarks. The ability of the targeting models to improve upon the naïve benchmarks does not deteriorate monotonically with the largest deviations from the training-data means. The distance- and model-driven targeting methods both perform best on carrier routes where the \textit{Maximum Deviation} is 1.5–2 standard deviations from the training-data mean. This is the group of carrier routes that is best represented in the training data (Figure 6).

Among carrier routes with larger \textit{Maximum Deviations} from the training data means, the targeting methods add essentially no value over the naïve benchmarks. Perhaps more surprisingly, we also see that the targeting methods add no value in carrier routes that have the smallest deviations from the training-data means.

We note that this last finding cannot simply be attributed to these carrier routes being less valuable. In Figure 7, the profits are all indexed against the most profitable uniform policy for that group of carrier routes. This benchmark controls for the variation in the relative value of the groups of carrier routes. When the 13 targeting variables all have values close to the training data mean, none of the targeting methods beat the naïve benchmark. Instead, it appears that a tight grouping around the training-data mean is another form of covariate shift. We see from

\textbf{Figure 5.} The Average Stage 2 Profit When Grouping the Households According to Whether They Are Inside or Outside the Range of the Training Data and When Pooling Using the Taxonomy of Methods

\textbf{Notes.} Profits are indexed to 100 for the most profitable uniform condition (in that group of carrier routes). We categorize the households in the Stage 2 validation data as falling inside the range of the Stage 1 training data if they have values on all 13 targeting variables within two standard deviations of the average value in the training data. The error bars represent 95\% confidence intervals.
Figure 6 that fewer than 14% of the training-data carrier routes have values on all 13 targeting variables that are tightly grouped within one standard deviation of the training-data mean. Because this region of the parameter space is not well represented in the training data, the targeting methods have relatively little information to make predictions in this region of the parameter space.

For completeness, we also investigated which targeting variables most frequently shifted between the two stages of the study. The most common deviations are Income and Home Value (higher in the validation data), distance to the competitors’ and retailer’s own stores (higher in the validation data), and the proportion of past trialists in the carrier route (higher in the validation data). These findings are summarized in the online appendix, where we also report which deviations had the largest impact on the performance of the targeting methods.

In the next subsection, we analyze how the methods performed as the underlying demand conditions varied between Stages 1 and 2.

5.2. Concept Shift

The interval between the first mailing date in Stage 1 and the first mailing date in Stage 2 was just over 6 months. In this intervening period, it is possible (even likely) that underlying demand conditions changed in different ways in different carrier routes. This nonstationarity could lead to changes in how prospective customers responded to the promotions. The machine-learning literature refers to this as “concept shift.” In this section, we investigate how concept shift affected the relative performance of the targeting methods.

Our discussion of concept shift proceeds in the following steps. First, we provide initial evidence of concept shift by comparing the outcome of the uniform policies in Stages 1 and 2. Second, we construct a measure of how underlying demand conditions changed between the two stages of the study. Changes in underlying demand conditions are one source of concept shift, so this measure provides an indicator of which carrier routes were most likely to experience concept shift. Third, we support our claim that underlying demand changes are associated with concept shift by comparing our initial measure of concept shift (the differences in the Stage 1 and 2 uniform policy outcomes) with our measure of changes in underlying demand conditions. Finally, we compare the performance of the seven optimized policies in Stage 2 when grouping the carrier routes using our measure of demand changes. The methods all perform worse when there are positive or negative changes in underlying demand, compared with when demand changes are flat. This is true for all three types of models, but the deterioration in performance is particularly large for the model-driven methods. We start by providing initial evidence of concept shift by comparing the performance of the uniform policies in Stages 1 and 2.

5.2.1. Initial Evidence of Concept Shift.

As initial evidence of concept shift, in Figure 8, we compare how the Lift in Profits attributable to the $25-paid and 120-day-trial promotion conditions varied between Stages 1 and 2. The Lift in Profits is calculated as the average profit in the promotion condition minus the average profit in the no-mail control condition. In this figure (and throughout this subsection), we restrict attention to the 234 carrier routes that received uniform treatments in both stages of the study. Focusing on this common sample of carrier routes essentially eliminates covariate shift, as there was almost no variation in the covariates within a carrier route between the two stages. Any remaining difference in the performance of the promotions across the two stages can thus be attributed to concept shift. To protect confidentiality, in Figure 8 and the other findings

**Figure 7.** The Average Stage 2 Profit When Grouping the Carrier Routes According to the Largest Deviation (Across the Targeting Variables) from the Average in the Training Data (measured in Training Data Standard Deviations) and When Pooling Using the Taxonomy of Methods

Notes. The profits are benchmarked at 100 using the most profitable uniform policy (in that group of carrier routes).
reported in this subsection (5.2), we multiply the profits by a (common) random number.

The findings reveal an important difference between the Stage 1 and Stage 2 results for these 234 carrier routes. The Lift in Profits attributable to the promotions were positive in Stage 1 but negative in Stage 2. The differences in these outcomes between the two stages could reflect a wide variety of factors, including seasonality, wear-in or wear-out of the promotions, competitors’ actions, or other activities by the retailer. Whatever the reason, these differences are examples of concept shift that could affect the performance of the targeting models. Although the average differences between Stage 1 and Stage 2 are only marginally significant (or less), they do suggest that our data provide an opportunity to understand how robust the seven targeting methods are to concept shift in a real-world marketing application.9

5.2.2. Measuring Changes in Underlying Demand Conditions. To study the impact of concept shift, we first quantify how underlying demand conditions changed between Stages 1 and 2. We construct a demand change measure using purchases by existing customers. In particular, we identify customers who had been members for at least 5 years at the start of Stage 1. Using these existing customers, we calculate total revenue during Stage 1 and total revenue during Stage 2 for each of the retailer’s stores. We then construct a measure of Revenue Change for each store:

\[
\text{Revenue Change} = \frac{(\text{Stage 2 Revenue} - \text{Stage 1 Revenue})}{0.5 \times \text{Stage 1 Revenue} + 0.5 \times \text{Stage 2 Revenue}}.
\]

Using the average of Stage 1 and 2 revenue as the denominator ensures that increases and decreases are treated symmetrically. Variation in this measure may result from almost any local factor, including macroeconomic variation, seasonality, competitors’ actions, or exposure to promotions. Our findings are robust to how this measure is constructed. For example, if we use all existing customers who were members prior to the start of the study, we obtain a very similar pattern of results. We also obtain similar results if we restrict attention to revenue from a common set of existing customers who made purchases in both Stage 1 and Stage 2. This ensures that the findings are not affected by attrition of existing customers from the panel.

Each carrier route is associated with a single store (the correspondence between the stores and the carrier routes is defined by the retailer), and our 234 carrier routes map to 15 different stores. The distribution of Revenue Change across these 15 stores is summarized in Figure 9, where we use different colored shading to group the stores as follows:10

- **Negative Growth**: Revenue Change less than $-0.02$
- **Flat Growth**: Revenue Change between $-0.02$ and $0.02$
- **Positive Growth**: Revenue Change over $0.02$

The Revenue Change measure is not a direct measure of concept shift. Instead, it measures changes in underlying demand conditions, which is not the same as the response to the promotions. Our assumption is that changes in demand conditions contribute to concept shift, and so we use Revenue Change as an indicator of which carrier routes were most likely to experience concept shift. We investigate this assumption next.

5.2.3. Concept Shift and Changes in Underlying Demand Conditions. To support our claim that Revenue Change is associated with concept shift, we conducted a preliminary analysis using the three uniform
mailing conditions. In particular, we repeated our earlier analysis of the Lift in Profits for the two promotions using the same 234 carrier routes. However, we now calculate the Lift in Profits separately for the 53 Negative Growth carrier routes, the 50 Flat Growth carrier routes, and the 131 Positive Growth carrier routes.

Changes in underlying demand conditions could affect the response to the three experimental conditions in unpredictable ways. Therefore, we do not make a specific prediction about how the Lift in Profits varies between Stages 1 and 2 across the different Revenue Change groups. Instead, we simply report the change in the Lift in Profits for each group. To do so, we first calculate the difference in profit between the promotion condition and the no-mail control (this is the Lift in Profits). We do this separately for the two promotion conditions ($25 paid and 120-day trial) and for the carrier routes in the different Revenue Change groups. We then calculate the change in the Lift in Profits between Stages 1 and 2 for each group. These differences are reported in Figure 10. For example, the figure reports that, compared with the no-mail control, the $25 paid promotion generated a Lift in Profits that was $1.05 smaller in Stage 2 than in Stage 1 in carrier routes with negative Revenue Growth.11

We see clear evidence that concept shift impacted the profitability of the two promotions. The impact was different for the two types of promotions and also varied systematically across the Revenue Change groups. To evaluate how this concept shift could affect the accuracy of Stage 2 decisions made using the Stage 1 outcomes, it is helpful to distinguish between three types of decisions: (a) whether to mail the $25 paid promotion versus not mail, (b) whether to mail the 120-day trial versus not mail, and (c) whether to mail the $25 paid versus the 120-day promotion.

For the first decision, the concept shift in Figure 10 means that using the Stage 1 data to make Stage 2 decisions is likely to lead to errors in all three Revenue Change groups. The $25-paid promotion generates a smaller profit lift in Stage 2 than in Stage 1, and so training on the Stage 1 data will tend to result in overmailing the $25 paid promotion in Stage 2. This is particularly true for the carrier routes with negative Revenue Growth, because the change in Lift in Profit is particularly large in this group.

For the second decision, using the Stage 1 data to make Stage 2 decisions will lead to different types of errors in the different Revenue Growth groups. Training on the Stage 1 data will tend to result in undermailing the 120-day trial promotion to negative

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Figure 9. The Distribution of the Revenue Change Measure Across the 15 Stores Associated with the Carrier Routes That Participated in Both Stages of the Study

Notes. Each column represents a single store. The colors of the bars distinguish between Negative Growth, Flat Growth, and Positive Growth stores.

Figure 10. The Average Change Between Stages 1 and 2 in the Lift in Profit Attributable to Each Promotion Condition

Notes. The Lift in Profit is calculated as the average profit in the promotion condition minus the average profit in the no-mail control condition. The change between Stages 1 and 2 is calculated as Stage 2 minus Stage 1. The results are reported separately for the $25 paid and 120-day trial promotions. The analysis uses the 234 carrier routes that received uniform treatments in both Stages 1 and 2. To protect confidentiality, we multiply the profits by a (common) random number.
Revenue Growth groups (though this effect appears small), and over-mailing in the flat and positive Revenue Growth groups. The errors are likely to be particularly large in the carrier routes with positive Revenue Growth, as the change in Lift in Profit is noticeably larger in that group than in the other groups.

The third decision focuses on “what to mail,” which depends solely upon the relative profits in the $25-paid and 120-day-trial conditions. To isolate the concept shift that affects this decision, we calculate the difference in profits between the two promotion conditions. We then compare this profit difference in Stages 1 and 2 and report the findings in Figure 11.12

The changes in the relative profitability of the two promotions clearly vary across the three Revenue Change groups. In carrier routes with negative change in underlying demand, the 120-day-trial promotions were relatively more profitable than the $25-paid promotions in Stage 2 compared with Stage 1. The reverse was true for carrier routes with positive demand change. Relying on the Stage 1 data to decide “what to mail” in Stage 2 could lead to errors in carrier routes with positive or negative Revenue Change.

In contrast, in carrier routes for which Revenue Change is flat, the relative profitability of the two promotions did not change between Stages 1 and 2. In these carrier routes, this type of concept shift did not occur, and so the Stage 1 data provide accurate information about which promotion to mail in Stage 2. This has an important implication for the performance of the seven optimized policies. The seven methods had more accurate information to select which promotion to mail in carrier routes for which Revenue Change was flat, compared with carrier routes in which Revenue Change was positive or negative.

We have reported evidence of concept shift, together with evidence that concept shift varies across the three Revenue Change groups. We next evaluate how the performance of the seven optimized targeting methods varied across the three Revenue Change groups.

5.2.4. Revenue Change and the Performance of the Methods. In Figure 12, we compare how well the three groups of methods performed when Revenue Change was negative or positive, compared with when it was flat. We report the Stage 2 performance of the different targeting methods within each Revenue Change group. The profit is indexed at 100 by using the most profitable uniform policy within each group. This indexing reveals how well the methods performed compared with the most profitable naive benchmark.

Concept shift anticipates that the performance of optimized policies will deteriorate if the underlying response function changes. One reason that the response function may change is because of changes in the underlying demand conditions. Our Revenue Change measure provides a measure of demand changes, and so concept shift would predict that the methods will perform best when Revenue Change is flat, but performance will deteriorate when Revenue Change is negative or positive. This is precisely what we see in Figure 12. Both positive and negative demand changes are associated with lower performance (relative to the naive benchmark) than flat demand growth. This is true for all three types of targeting methods.

The poor performance of the targeting policies when Revenue Change is positive or negative cannot be attributed to lower-value customers in these carrier routes. Recall that the findings in Figure 12 are indexed against the most profitable uniform policy within each group of carrier routes. This controls for differences in the absolute value of the customers in each group.

The deterioration in performance appears to be larger for the model-driven methods than for the other methods. In the online appendix, we formally...

Notes. The difference in profits is calculated as the 120-day trial Profit minus the $25 paid Profit. The change between Stages 1 and 2 is calculated as Stage 2 minus Stage 1. The analysis uses the 234 carrier routes that received uniform treatments in both Stages 1 and 2. To protect confidentiality, we multiply the profits by a (common) random number.
compare the deterioration in the performance across methods. The findings confirm that profits are lower in carrier routes for which revenue among existing customers changed between the two stages. This is true for either positive or negative Revenue Change. Moreover, the deterioration in profit between the Flat Growth and Positive Growth carrier routes is larger for model-driven methods than distance-driven methods. We also see that model-driven methods deteriorate more than classification methods when Revenue Change is negative (compared with when it is flat). Although the model-driven methods outperform the distance-driven and classification methods when there is little evidence of concept shift (revenue change is flat), they perform no better when concept shift is present (revenue change is negative or positive).

Because in Figure 12, we are only using 234 carrier routes, the sample size is relatively small, and so the figure is constructed at the taxonomy level (which requires less data). For completeness, we report results at the method level in the online appendix. Results at the taxonomy level and at the method level are consistent. In the negative-growth group, six of seven methods perform worse than the benchmark uniform policy (three are significantly worse). In the flat-growth group, six of seven methods perform better than the benchmark uniform policy (two are significantly better). In the positive-growth group, seven of seven methods perform worse than the benchmark uniform policy (four are significantly worse).

The evidence that the performance of the model-driven methods is more sensitive to demand changes than the other methods is consistent with the covariate shift results reported in the previous subsection (Section 5.1). In the absence of covariate shift or concept shift, the model-driven methods yield the largest improvements over the naive benchmarks. However, as the quality of the data deteriorates due to either covariate shift or concept shift, the advantages of using the model-driven methods quickly disappear. In the next set of results in this section, we analyze how the methods performed when the quality of the training data deteriorated due to aggregation.

5.3. Aggregation of the Targeting Variables
When targeting existing customers, firms can use past purchasing history to make targeting decisions. In the absence of individual purchasing histories, firms generally rely upon demographic variables, which are typically aggregated across census blocks, ZIP codes, or carrier routes. This feature is an important difference between targeting prospective customers and targeting existing customers. In this section, we investigate how this aggregation affects the performance of the targeting methods.

In the literature review, we recognized that aggregate models may perform better or worse than less-aggregate models under different conditions. Aggregation can lead to a loss of information, resulting in worse performance. However, aggregation can also improve performance by mitigating measurement errors. In this subsection, we provide evidence of both negative and positive effects of aggregation on the performance of machine-learning methods. Aggregation undermines the performance advantage of model-driven methods. However, it also results in significant improvements in the performance of SVM, which is trained more accurately for larger carrier routes than for smaller carrier routes.

Because the number of households in a carrier route varies across carrier routes, the degree of aggregation also varies. For households in carrier routes with relatively few households (small carrier routes), the targeting variables contain more information about the households than in carrier routes with many households. To investigate how the precision of the information affected the outcomes, we calculated the findings separately using a median split of the number of households in each carrier route. The findings are summarized in...
Figure 13, where we report findings for each of the 10 treatments, and in Figure 14, where we group the methods using our taxonomy.

In the smaller carrier routes, where the targeting variables are more informative, the two model-driven targeting methods (Lasso and FMM) perform better than the other methods. This improvement is particularly clear when grouping the methods using our taxonomy of methods. This suggests that the model-driven methods make the best use of the increased precision of the information in the targeting variables in smaller carrier routes. Notice that this finding cannot be explained simply by smaller carrier routes being more profitable. We would expect this to benefit all methods.

However, in the larger carrier routes, where the demographic variables contain less precise information about each household, all targeting methods perform similarly. Notably, none of them outperform the benchmark of uniformly mailing the $25-paid promotion to every household. The implication is that when the carrier routes are large, the targeting variables provide so little information that none of the targeting methods can improve upon a naïve benchmark. Moreover, this deterioration in performance when there is more aggregation is more pronounced for the model-driven methods than for the other methods.

As a robustness check, we repeated the analysis using the top and bottom 10% of carrier routes and using the top and bottom 25% of carrier routes. The findings are reported in the online appendix. The pattern of findings is similar, although using smaller slices of the data introduces more noise. There is also one notable new result: SVM performs significantly better in the largest 10% of carrier routes compared with the smallest 10%.

The source of this result is the “imprecise label” problem that SVM is susceptible to, as well as the low response rate to mailed promotions. Recall that in Stage 1, within any carrier route, all three actions (no mail, $25 paid offer, and 120-day free trial) were received by some households. The profitability of the actions that mail can only be realized in carrier routes where some responses to promotions were received. Because of the low response rate, this is more likely in larger carrier routes than in smaller carrier routes. As a result, the training labels used by SVM in Stage 1 are more likely to be mailing actions in larger carrier routes than in smaller carrier routes. SVM, therefore, is trained to mail to a greater extent to larger carrier routes and to a lesser extent to smaller carrier routes.

In particular, within the largest 10% of carrier routes in Stage 2, SVM recommended no mail to 77.86% of the households, and the $25 paid offer to 22.14% of the households. Within the smallest 10% of carrier routes in Stage 2, SVM recommended no mail to 80.60% of the households, the $25 paid offer to 17.86% of the households, and the 120-day free trial to 1.54%. The smaller carrier routes are undermailed by the SVM more so than the larger carrier routes. We discuss these issues in greater detail in the next subsection.

We can also compare the type of promotion that SVM recommended mailing. In smaller carrier routes, SVM was less likely to recommend the $25 paid promotion than in larger carrier routes. This happens because responses to either promotion are rare in smaller carrier routes. As a result, when training SVM in smaller carrier routes, it is not as obvious as in larger carrier routes that the $25 paid offer dominates the 120-day free trial.

This argument explains why the performance of SVM in larger carrier routes is better than in smaller carrier routes. This effect is pronounced when we compare the largest 10% against the smallest 10% of carrier routes. However, it is counteracted by the effect of loss of information through higher aggregation when we compare the largest 50% against the smallest 50% of carrier routes.

We conclude by recognizing that, beyond interpreting aggregation as a measure of loss of information in the targeting variables, we also see evidence of a positive effect of aggregation. Aggregation improved the

Figure 13. The Average Profits Earned in the Stage 2 Treatment Condition When Grouping the Carrier Routes According to Whether They Contain More or Less Than the Median Number of Households

Notes. The profits are indexed to 100 in the No Mail–Below Median Size data point. Complete findings are reported in the online appendix.
The erosion in the performance of the model-driven methods is consistent with our interpretation that the poor performance of the classification methods is at least partly attributable to loss of information. We also discuss modifications to the classification methods that have been proposed in the machine-learning literature to address this limitation.

To help understand why the classification methods performed poorly in our study, we start by considering the following simplified setting. Suppose the training set consists of \( N \) carrier routes, each described by targeting variables \( x_i \in \mathbb{R}^L \). For each carrier route \( i \) in the training set, we know the profit outcomes for the no mail and mail treatments, \( (y_i^{\text{no mail}}, y_i^{\text{mail}}) \). We define a matrix \( X \in \mathbb{R}^{N \times p} \) and vectors \( y_i^{\text{no mail}} \in \mathbb{R}^{N \times 1} \) and \( y_i^{\text{mail}} \in \mathbb{R}^{N \times 1} \) to capture the targeting variables and the profit outcomes of all customers in the training data. We also have a new carrier route with targeting variables \( x_{\text{new}} \) for which we want to select an optimal treatment.

In the model-driven and distance-driven (regression-based) methods, we use \( (X, y_{i}^{\text{no mail}}, y_{i}^{\text{mail}}) \) to train two models that predict \( (y_{i}^{\text{no mail}}, y_{i}^{\text{mail}}) \) given \( x_i \). We then predict \( (\tilde{y}_{\text{new}}^{\text{no mail}}, \tilde{y}_{\text{new}}^{\text{mail}}) \) for \( x_{\text{new}} \) and assign to a new observation the treatment that yields the largest predicted profit.

In the classification methods, we first transform \( (y_{i}^{\text{no mail}}, y_{i}^{\text{mail}}) \) to \( t^* \), where \( t_i^* = \arg\max_{t} \tilde{f}(y_i) \) is the optimal treatment in hindsight for carrier route \( i \) in the training set. We then use \( (X, t^*) \) to train a classifier that predicts \( t_i \) given \( x_i \) and assign to a new observation the treatment that the classifier predicts is optimal: \( t_{\text{new}}^* = \tilde{f}(x_{\text{new}}) \).

The explanation for why the classification methods perform poorly focuses on the transformation \( (y_{i}^{\text{no mail}}, y_{i}^{\text{mail}}) \) to \( t^* \) and on the training of the prediction function \( \tilde{f}(\cdot) \).

We illustrate the explanation using an example. Assume that the carrier routes are identical, so that they are not distinguishable by targeting variables \( X \). If a household responds to a promotional mailing, the firm earns $1,000 after deducting costs. If the
household does not respond, the firm loses $1 representing mailing and printing costs. Not mailing yields a payoff of zero with certainty.

Consider first a model with a 100% response rate. If all households that were mailed respond to the mailing, the firm earns $1,000 from each of these; customers and zero profit from the customers who were not mailed. Regression-based methods will predict that mailing yields an expected profit of $1,000 per customer and that not mailing yields an expected profit of zero per customer. The regression-based methods will therefore correctly recognize that mailing is more profitable than not mailing in every carrier route.

Classification methods will also recognize that in hindsight mailing is on average more profitable than not mailing in every carrier route. The transformation \((y^\text{no mail}, y^\text{mail}) \rightarrow t^\star\) will result in every carrier route in the training data receiving a label indicating mailing was the most profitable policy \((t^\star = \text{mail})\). Consequently, the classification methods will also correctly recommend mailing to every carrier route. We conclude that with a 100% response rate, both types of methods will recommend the optimal policy.

Now assume that the probability a household (in any carrier route) responds to a mailing is just 1%. Assume further that every carrier route has 100 households, and in the training data a randomly selected subsample of 50 households receives promotional mailings. The remaining households are not mailed. Regression-based methods will predict that mailing yields an expected profit of $9.01 per household ($1,000 \times 0.01 - $1 \times 0.99) and correctly recognize that mailing is more profitable than not mailing.

In contrast, classification methods will compare the profits earned from mailing and not mailing in each carrier route. If at least one customer responds, the total profits exceed the mailing costs, in which case the carrier route receives a label indicating that mailing is the most profitable policy \((t^\star = \text{mail})\). In contrast, if no customer responds, the label indicates that not mailing is more profitable in that carrier route \((t^\star = \text{no mail})\). With 50 customers receiving mailings and a 1% probability of a response, the probability there is at least one response is 39.5% (i.e., \(1 - 0.99^{50}\)), assuming independence. In expectation, 39.5% of the carrier routes receive a label mail, and the remaining 60.5% receive a label no mail. Because the carrier routes are not distinguishable by \(X\), and not mailing is optimal more frequently than mailing, the classification methods will incorrectly recommend not to mail.

This error reflects a loss of information due to the transformation \((y^\text{no mail}, y^\text{mail}) \rightarrow t^\star\). The transformation recognizes which treatment performed best for each carrier route in the training data, but discards information about the magnitude with which it outperformed the other treatments.

The machine-learning literature has recognized this limitation and characterized when it is most likely to lead to suboptimal policies. Errors are likely when the data are “imbalanced” (i.e., the two labeled classes have different sizes in the training set), and the cost of errors is asymmetric. Asymmetric costs arise when the cost of a false positive (mailing when there is no response) is very different than the cost of a false negative (not mailing when there would be a response).

Data imbalance and asymmetric costs are clearly illustrated in our example. Recall that if 100% of the customers responded to the promotion mailing, the classification methods recommend the correct policy. They only make an error when the response rate is so low that the majority of carrier routes do not receive a single response. Notice also that if the profit when a customer responds to a mailing were identical to the profit lost when a customer does not respond to a mailing, then the classification methods would also perform well. It is the difference in these outcomes that makes the costs “asymmetric.”

Targeting prospective customers with direct mail yields a low average response rate, but a large profit when customers do respond. This makes the imbalanced data with asymmetric costs issue particularly relevant in our setting. This is not true for all marketing problems. For example, when targeting existing customers, average response rates tend to be a lot higher than for prospects, while using a sales force to target customers (instead of direct mail) can also increase response rates. In both examples, we would expect data that are a lot less imbalanced. Moreover, for existing customers, the difference in long-run profits from customers who respond to a promotion, versus those who do not, may be relatively small. If the response to a promotion results in temporal substitution from future demand, the response to the promotion may result in little variation in long-run profits. In these examples, the cost of errors is more symmetric.

Our illustrative example can also be used to highlight an additional characteristic that makes targeting prospective customers even more challenging for classification methods. The labeling of the optimal policy in each carrier route is made based on a relatively small sample of households in each carrier route. This introduces a finite sample problem, which is not just a source of variance, but also a source of bias. We can illustrate this bias by assuming that instead of 100 households per carrier route with 50 receiving the mailings in the training data, there are 200 households per carrier route and 100 receive the mailings. Mailing is still profitable in a carrier route if at least one household responds to the mailing. With 100 households receiving mailings, the probability that at least one household will respond in a carrier route is 63.4% (i.e., \(1 - 0.99^{100}\)), assuming
independence. As a result, we would expect that over half of the carrier routes (63.4%) would receive a label indicating that “mail” was the most profitable action, and the classification methods will now correctly recommend mailing to every carrier route. This example confirms that the size of the training data does not just contribute to variance in the recommended policy; it can also introduce bias by changing the expected policy. The machine-learning literature refers to this as an “imprecise label” problem (Frénay and Verleysen 2014).

These arguments are reflected in our performance comparison using the largest and smallest 10% of carrier routes (these results are discussed at the end of the previous subsection and reported in the online appendix). SVM performed significantly better in the largest carrier routes than in the smallest carrier routes. We can further illustrate this argument by counting the number of households that received the $25 paid promotion in each Stage 1 carrier route. We then divide the Stage 1 carrier routes into two subsamples using a median split of this count (for ease of exposition, we will label them the “large” and “small” carrier routes). Within each subsample, we compare how often the promotion was more profitable than the no mail control. Among the large carrier routes, the profits earned in the $25 paid treatment exceeded the no-mail control in 32.9% of the carrier routes. However, among the small carrier routes, just 24.9% of carrier routes had higher profits in the $25 paid treatment than in the control. The difference in these proportions is highly significant (p < 0.0001) and is replicated when we conduct the same analysis for the 120-day free trial. For large carrier routes, it appears to the classification methods that mailing is profitable more frequently than in small carrier routes. However, this is an artifact of the transformation (\(y^\text{no mail} = y^{25}, y^{120\text{-day}}\)) \(\rightarrow t^s\), and will occur even if the optimal policy is the same in large and small carrier routes.

This bias leads to suboptimal policies. As the no mail control condition is more profitable (in hindsight) in most of the carrier routes in the training data, the classification methods recommend not mailing to too many carrier routes. This is precisely what we see. SVM and CHAID recommend not mailing either promotion to 82.2% and 66.3% of the Stage 2 carrier routes, respectively. In contrast, the model-driven and distance-driven (regression-based) methods choose not to mail to 25.3% and 22.3% of carrier routes respectively.

The machine-learning literature has proposed two approaches to address these problems. One class of methods involves preprocessing the training data (these are sometimes call external solutions), whereas the second approach involves adjusting the decision rule (these solutions are sometimes called internal solutions).

The external solutions involve sampling from the universe of data in the training data. Many different sampling methods have been proposed (see He and Ma 2013 for a collection of papers describing different resampling methods). For example, Batuwita and Palade (2010) study SVM and recommend first estimating the prediction function \(\hat{t}(\cdot)\) using all of the data in the training sample. This original estimate is then used to select the data points (carrier routes) lying close to the hyperplane that separates the different classes of observations (in X-space). By oversampling in this region and reestimating the prediction function, the data imbalance issue is addressed, and performance may be improved.

Internal methods incorporate the asymmetric costs of errors into the policy design (see, e.g., Eitrich and Lang 2006). In particular, if the cost of a false negative is higher than the cost of a false positive, then the decision rule can be adjusted to give more weight to avoiding false negatives (or vice versa). In our example, the cost of a false negative (not mailing to a carrier route that would yield one or more responses) is much higher than the cost of a false positive (mailing to a carrier route that does not yield any responses). The decision rule could be adjusted to account for this by recommending mailing to all carrier routes whenever at least a third of the carrier routes in the training data receive the label mail (instead of at least half of the carrier routes). In practice, this adjustment is made by adjusting the prediction function \(\hat{t}(\cdot)\), which shifts the separating hyperplane distinguishing the different classes of observations. Our illustration highlights that the cost adjustment could also potentially account for the bias introduced by the imprecise labels problem.

As we discussed, asymmetric costs, imbalanced data, and label imprecision are very relevant when prospecting for new customers and are also likely to arise in other customer-targeting problems. Although there is now an extensive machine-learning literature that proposes solutions to these problems, the problems and the proposed solutions have received little attention in marketing. The proposed modifications are likely to improve the performance of the classification methods, but it is unlikely that a moderately sophisticated retailer would implement these solutions. We believe that the findings we report are representative of the performance that many retailers will obtain when using these classification methods.

For completeness, in the next section, we extend the range of our comparisons to include methods that a more sophisticated retailer might use. This includes a modified version of SVM that addresses the problems we have described in this subsection.
6. Comparing Methods That a More Sophisticated Retailer Might Use

In the introduction, we described the retailer that participated in this study as a firm with revenue in the tens of billions USD, with a well-organized and extensive data warehouse and a team of data analysts. We also observed that, before this study, the firm’s data analysts built targeting models using OLS. The team was not ready to implement the seven machine-learning methods that we have discussed in the previous sections of this paper. However, we recognize that there are retailers that are capable of implementing even more sophisticated methods than the methods we have discussed. In this section, we will compare the performance of five additional methods.

The five additional methods include: XGBoost, neural networks, random forest, adjusted SVM, and Lasso with interactions. We summarize each of these methods in the online appendix. The adjusted SVM asymmetrically penalizes false positives and false negatives, while training the classification model. This adjustment accounts for and mitigates the asymmetric costs and imprecise label problems described in Section 5.4. Lasso with interactions incorporates in the model specification the complete set of pairwise interactions between the 13 targeting variables.

The five additional methods were not implemented in their own treatment conditions in the Stage 2 experiment. However, we can still evaluate them using the three uniform treatment conditions. The evaluation approach is described in detail in two recent papers by Hitsch and Misra (2018) and Simester et al. (2019).

The approach uses “counterfactual policy logging.” Counterfactual policy logging tracks which actions a targeting policy would have recommended to participants, regardless of what action the participants actually received in the Stage 2 experiment. Participants are then segmented according to the recommended actions from that policy (or pair of candidate policies). For example, we used segmentation based on counterfactual policy logging in Section 4.2, where we compared Lasso to the uniform $25 paid policy after segmenting participants using Lasso’s recommended actions.

Consider a new targeting policy designed using Stage 1 data. This targeting policy recommends an action for each participant in the three uniform treatment conditions in the Stage 2 experiment. These are the counterfactual policy assignments. To evaluate the new policy, within each segment, we match the actions recommended by the policy with the subgroup that actually received that action. The randomization of customers between the three uniform treatments ensures that, within each segment, there are equivalent subgroups of participants that received each of the three actions.

We can then aggregate the average Profit from these selected subgroups across the segments. When aggregating the average performance across segments, we weight by the proportion of the population for which each action was recommended. This is an unbiased estimate for the performance of the targeting policy (see Simester et al. 2019 for additional details).

6.1. Evaluation of the Additional Methods

We trained the five additional methods using the same Stage 1 training data that we used to train the original seven methods. We then evaluate them with data from the Stage 2 uniform policies using the procedure summarized above. Table 2 reports the increase (decrease) in average Profit for each of the five additional policies compared with standard Lasso.

To preserve confidentiality, the Profit improvements are indexed to 100 for the standard Lasso average Profit.

There are two findings of interest. First, the performance of the SVM classifier greatly improves when adjusting the SVM cost function. Without adjustment, we saw in Figure 1 that the average performance of SVM is significantly lower than the performance of standard Lasso. However, after adjusting for the asymmetric cost of false positives and false negatives, the average Profit from SVM is no longer significantly different than the average profit from standard Lasso.

More generally, none of the five additional methods provide significant improvements in average Profit compared with standard Lasso. A tempting conclusion is that the performance of Lasso is simply very good and hard to improve upon. However, the findings we have reported in the paper also suggest an alternative explanation. It is possible that other methods make even better use of the information in the training data, but their performance is also even more susceptible to covariate shift and other data challenges.

To investigate this second explanation, we repeated the covariate shift, concept shift, and aggregation analyses for the five additional methods. We report

| Method          | Profit difference | Standard error |
|-----------------|-------------------|----------------|
| Neural network  | −2.956            | 2.526          |
| XGBoost         | −1.785            | 2.368          |
| Adjusted SVM    | −1.166            | 2.314          |
| Random forest   | −0.589            | 2.717          |
| Lasso with interactions | 0.271 | 0.560 |

Notes. The standard errors of these Profit differences are also reported. To preserve confidentiality, profits are indexed to 100 for the standard Lasso average Profit. Negative values indicate that standard Lasso is more profitable than the other policies.
the findings in the online appendix. Most methods perform similarly to standard Lasso when the training data are ideal, which supports the first explanation that the performance of Lasso is hard to improve upon. We also see support for the second explanation. Across the covariate shift, concept shift, and aggregation analyses, our findings with the five additional methods are consistent with the pattern in Section 5. Methods that make the best use of the information in the training data have the greatest deterioration in performance when the information in the training data deteriorates.

7. Conclusions

As more firms embrace field experiments to optimize their marketing activities, the focus on how to derive more value from field experiments is likely to intensify. One way to derive additional value is to segment customers and evaluate how to target different customers with different marketing treatments. Fortunately, the literature on customer segmentation and targeting methods is vast, and so firms have a broad range of methods from which to choose. However, the literature offers little guidance as to which of these methods are most effective in practice.

In this paper, we have evaluated seven widely used segmentation methods using a series of two large-scale field experiments. The first field experiment is used to generate a common pool of training data for each of the seven methods. We then validate the optimized policies provided by each method in a second field experiment. Our detailed comparison of the methods reveals an important general finding. Model-driven methods perform better than distance-driven and classification methods when the data are ideal. However, they also deteriorate faster in the presence of covariate shift, concept shift, and information loss through aggregation. Intuitively, the model-driven regression methods make the best use of the available information, but the performance of these methods is more sensitive to deterioration in the quality of the information.

We also investigated why the model-driven and distance-driven methods outperformed the classification methods in our setting. Classification methods perform poorly when there is a low probability of a response, but each response is very profitable. We describe modifications to the classification methods that have been proposed in the machine-learning literature to address these challenges.

Endnotes

1 One possible source of past purchasing data for prospective customers is purchasing from competitors. However, these opportunities are relatively limited.
2 Sugiyama and Kawanabe (2012) provide a comprehensive review of this literature.
3 When interpreting the results, we recognize that the size of the carrier route may be related to other carrier-route features.
4 Different data-extraction processes are used to identify new members and track purchases.
5 Charging a constant markup is common for this type of retailer.
6 A small number of customers purchased products (primarily cigarettes) from the retailer to (presumably) sell at their own retail locations. This introduced outliers to measures of store revenue. At the suggestion of the retailer, store revenue in the first 77 days that exceeded $15,000 was truncated to $15,000. This affected just eight of the 4,119,244 observations in the Stage 2 validation data. It did not affect any of the 1,185,141 observations in Stage 1.
7 In this analysis, we focus on the maximum deviation across the 13 targeting variables. However, we also obtain similar findings when we repeat the analysis using the average deviation across the 13 variables.
8 The 120-day benchmark was used for the Under 1 group, the No Mail benchmark was used for the 1 to 1.5 group, and the $25 benchmark was used for the remaining groups.
9 The t-values comparing the average profit between Stage1 and Stage 2 are 1.60 (120-day Trial, p < 0.12) and 1.53 ($25 paid, p < 0.13). When comparing both promotions with the No Mail Control between Stage 1 and Stage 2, the t-value of the difference is 1.80 (p < 0.08). The Stage 2 revenue was higher in the promotion conditions than in the No Mail Control. However, the profits in the promotion condition were lower than in the control because the profit contributed by the incremental revenue was less than the cost of mailing the promotions.
10 We also investigate using thresholds of −0.01 and 0.03 to balance the size of the groups. This yielded a similar pattern of results.
11 Recall that we multiply the profits by a random number.
12 This is equivalent to calculating the difference between the Profit Lift: $25 paid and Profit Lift: 120-day columns in Figure 10.
13 Note that although we do not include the size of the carrier route as a covariate, other targeting variables are correlated with carrier-route size, notably Single Family (correlation −0.385), Multi-Family (correlation 0.376), and Comp. Distance (correlation −0.352).
14 The difference between the 77.86% no-mail percentage for the largest 10% of carrier routes, and the 80.60% no-mail percentage for the smallest 10% of carrier routes, is statistically significant.
15 For example, the Direct Marketing Association reports that average direct marketing response rates are approximately three times higher when targeting existing customers compared with prospective customers (Direct Marketing Association 2005).
16 Temporal demand substitution in response to promotions is well studied in marketing (see, e.g., Krishna 1992, 1994; Thompson and Noordewier 1992). One dramatic example occurred in 2005 when the three U.S. domestic automobile manufacturers all offered a promotion in which customers could buy at the “employee prices.” This resulted in a record increase in sales at the time of the promotion, but this simply pulled demand forward, so that there was almost no change in any of the firms’ annual sales (Busse et al. 2010).
17 For the 120-day free trial, among the larger carrier routes (for which the number receiving the 120-day promotion was above the median), the promotion was more profitable than the no-mail control in 29.6% of the carrier routes, compared with 24.0% in the smaller carrier routes. This difference is again highly significant.
18 Although not in a marketing journal, Kim et al. (2013) recognize the data imbalance problem and use random undersampling methods to reduce the degree of imbalance.

19 We also use a similar approach in the online appendix when investigating why Lasso chose not to mail to some carrier routes.

20 The estimation uses double machine learning to address the overfitting and regularization biases (Chernozhukov et al. 2018) and includes the 13 targeting variables as covariates (see Simester et al. 2019).

References

Abhishek V, Hosanagar K, Fader PS (2015) Aggregation bias in sponsored search data: The curse and the cure. Marketing Sci. 34(1):59–77.

Aigner DJ, Goldfeld SM (1974) Estimation and prediction from aggregate data when aggregates are measured more accurately than their components. Econometrica 42(January):113–134.

Aigner DJ, Goldfeld SM (1973) Simulation and aggregation: A reconsideration. Rev. Econ. Stat. 55(February):114–118.

Alaiz-Rodriguez R, Japkowicz N (2008) Assessing the impact of changing environments on classifier performance. Bergler S, ed. Adv. Artificial Intelligence (AI 2008), Lecture Notes in Computer Science, vol. 5032 (Springer, Berlin), 13–24.

Andrews RL, Currim IS, Leelang PSH (2011) A comparison of sales response predictions from demand models applied to store-level versus panel data. J. Bus. Econom. Statist. 29(2):319–326.

Auer P, Warmuth MK (1998) Tracking the best disjunction. Machine Learn. 32(2):127–150.

Bald P, Brunak S (2001) Bioinformatics: The Machine Learning Approach (MIT Press, Cambridge, MA).

Batuwita R, Palade V (2010) Efficient resampling methods for training support vector machines with imbalanced datasets. 2010 Internat. Joint Conf. Neural Networks (IJCNN) (IEEE, Piscataway, NJ), 1–8.

Bellet A, Habrard A, Sebban M (2013) A survey on metric learning for feature vectors and structured data. Working paper, University of Southern California, Los Angeles.

Biau G, Gyorfi L (2005) On the asymptotic properties of a non-parametric l/sub 1/-sub 1/-test statistic of homogeneity. IEEE Trans. Inform. Theory. 51(11):3965–3973.

Bickel S, Scheffer T (2007) Dirichlet-enhanced spam filtering based on biased samples. Advances in Neural Information Processing Systems, vol. 19 (Curran Associates, Red Hook, NY), 161–168.

Borgwardt KM, Gretton A, Rasch MJ, Kriegel H-P, Schölkopf B, Smola AJ (2006) Integrating structured biological data by kernel maximum mean discrepancy. Bioinformatics 22(14):e49–e57.

Busse MR, Simester DI, Zettelmeyer F (2010) “The best price you’ll ever get”: The 2005 employee discount pricing promotions in the U.S. automobile industry. Marketing Sci. 29(2):268–290.

Caputo B, Sim K, Furesjo F, Smola A (2002) Appearance-based object recognition using SVMs: Which kernel should I use? Proc. NIPS Workshop Stat. Methods Comput. Experiments Visual Processing Comput. Vision (Whistler, British Columbia) vol. 2002.

Castillo G, Gama J, Breda AM (2003) Adaptive Bayes for a student modeling prediction task based on learning styles. Brusilovsky P, Corbett A, de Rosis F, eds. Internat. Conf. User Modeling (Springer, Berlin), 328–332.

Chernozhukov V, Chetverikov D, Demirer M, Duflo E, Hansen C, Newey W (2017) Double/debiased/Neyman machine learning of treatment effects. Amer. Econom. Rev. 107(5):261–265.

Chernozhukov V, Chetverikov D, Demirer M, Duflo E, Hansen C, Newey W, Robins J (2018) Double/debiased machine learning for treatment and causal parameters. Econom. J. 21(1):C1–C68.

Delen D, Walker G, Kadam A (2005) Predicting breast cancer survival probability: A comparison of three data mining methods. Artificial Intelligence Medicine 34(2):113–127.

Dietterich TG, Widmer G, Kubat M, eds. (1998) Special issue on context sensitivity and concept drift. Machine Learn. 32(2).

Direct Marketing Association (2005) Statistical Fact Book (Direct Marketing Association, New York).

Edwards JB, Orcutt GH (1969) Should estimation prior to aggregation be the rule? Rev. Econom. Stat. 51(11):409–420.

Eitrich T, Lang B (2006) Efficient optimization of support vector machine learning parameters for unbalanced datasets. J. Comput. Appl. Math. 196(2):425–436.

Erdem T, Keane MP (1996) Decision-making under uncertainty: Capturing dynamic brand choice processes in turbulent consumer goods markets. Marketing Sci. 15(1):1–20.

Foekens EW, Leelang PSH, Wittink DR (1994) A comparison and an exploration of the forecasting accuracy of a loglinear model at different levels of aggregation. Internat. J. Forecast. 10(2):245–261.

Fréray B, Verleysen M (2014) Classification in the presence of label noise: A survey. IEEE Trans. Neural Networks Learn. Systems 25(5):845–869.

Friedman JH, Rafsky LC (1979) Multivariate generalizations of the Wald-Wolfowitz and Smirnov two-sample tests. Ann. Statist. 7(4):697–717.

Friedman J, Hastie T, Tibshirani R (2001) The Elements of Statistical Learning, Springer Series in Statistics, vol. 1 (Springer, New York).

Gama J, Zloibaitë I, Bifet A, Pechenizkiy M, Bouchachia A (2014) A survey on concept drift adaptation. ACM Comput. Surv. 46(4):1–37.

Gretna A, Borgwardt KM, Rasch MJ, Schölkopf B, Smola A (2012) A kernel two-sample test. J. Machine Learn. Res. 13(March):723–773.

Grunfeld Y, Griliches Z (1960) Is aggregation necessarily bad? Rev. Econom. Statist. 42(February):1–13.

Gupta S, Chintagunta P, Kaul A, Wittink DR (1996) Do household scanner data provide representative inferences from brand choices: A comparison with store data. J. Marketing Res. 33(4):383–398.

Hall P, Tajvidi N (2002) Permutation tests for equality of distributions in high-dimensional settings. Biometrika 89(2):359–374.

Hand DJ (2006a) Classifier technology and the illusion of progress. Statist. Sci. 21(1):1–14.

Hand DJ (2006b) Rejoinder: Classifier technology and the illusion of progress. Statist. Sci. 21(1):30–34.

Harries MB, Sammut C, Horn K (1998) Extracting hidden context. Machine Learn. 32(2):101–126.

Harries M, Horn K (1995) Detecting concept drift in financial time series prediction using symbolic machine learning. AI-Conference (World Scientific Publishing, Singapore), 91–98.

He H, Ma Y, eds. (2013) Imbalanced Learning: Foundations, Algorithms, and Applications (John Wiley & Sons, New York).

Helmold DP, Long PM (1991) Tracking drifting concepts using random examples. Warmuth MK, Valiant LG, eds. Proc. 4th Annual Workshop Comput. Learn. Theory (Morgan Kaufmann Publishers Inc., Burlington, MA), 13–23.

Helmold DP, Long PM (1994) Tracking drifting concepts by minimizing disagreements. Machine Learn. 14(1):27–45.

Herbster M, Warmuth MK (1998) Tracking the best expert. Machine Learn. 32(2):151–178.

Hitsch G, Misra S (2018) Heterogeneous treatment effects and optimal targeting policy. Working paper, University of Chicago, Chicago.

Indyk P, Motwani R (1998) Approximate nearest neighbors: Towards removing the curse of dimensionality. In Proc. 30th Annual ACM Symp. Theory Comput. (Association for Computing Machinery, New York), 604–613.

Jain A, Zongker D (1997) Feature selection: Evaluation, application, and small sample performance. IEEE Trans. Pattern Anal. Machine Intelligence 19(2):153–158.
