## Multistream Articulatory Feature-Based Models for Visual Speech Recognition

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Multistream Articulatory Feature-Based Models for Visual Speech Recognition

Kate Saenko, Karen Livescu, James Glass, and Trevor Darrell

Abstract—We study the problem of automatic visual speech recognition (VSR) using dynamic Bayesian network (DBN)-based models consisting of multiple sequences of hidden states, each corresponding to an articulatory feature (AF) such as lip opening (LO) or lip rounding (LR). A bank of discriminative articulatory feature classifiers provides input to the DBN, in the form of either virtual evidence (VE) (scaled likelihoods) or raw classifier margin outputs. We present experiments on two tasks, a medium-vocabulary word-ranking task and a small-vocabulary phrase recognition task. We show that articulatory feature-based models outperform baseline models, and we study several aspects of the models, such as the effects of allowing articulatory asynchrony, of using dictionary-based versus whole-word models, and of incorporating classifier outputs via virtual evidence versus alternative observation models.

Index Terms—Visual speech recognition, articulatory features, dynamic Bayesian networks, support vector machines.

1 INTRODUCTION

Visual speech recognition (VSR), also sometimes referred to as automatic lipreading, is the task of transcribing the words uttered by a speaker, given a silent video of the speaker’s mouth or face. Human speech perception makes significant use of both the acoustic and visual signals [22], and automatic speech recognition can also benefit from the addition of visual observations [32]. VSR may also be useful as a stand-alone task, when the audio is extremely noisy or not available. Previous work on VSR has largely used hidden Markov model (HMM)-based methods [32], analogously to standard approaches for acoustic speech recognition [14]. In these approaches, a separate HMM is used to model each basic linguistic unit and the HMMs are connected to form a finite-state graph of all possible utterances. The basic linguistic unit is typically either a word or a viseme, the visual correlate of an acoustic phoneme, or basic speech sound.

In HMM-based methods, each state can be thought of as a configuration of the vocal tract, or of the visible portion of the vocal tract in the case of visual speech recognition. Each configuration, however, corresponds to a combination of states of multiple speech articulators: the degree of lip opening, lip rounding, the position of the tongue, and so on. Articulatory parameterizations are often used in linguistics to describe phonological structure. For example, Fig. 1 shows one parameterization similar to the one used in articulatory phonology [4]. The parameters are often referred to as articulatory features (AFs). The AFs have been used in a number of models for acoustic speech recognition (e.g., [9], [17], [21]) and a benefit has been found in certain conditions for using separate classifiers of articulatory features rather than a single classifier of phoneme states [17].

In this paper, we explore the use of articulatory feature-based models for visual speech recognition. We use dynamic Bayesian network (DBN) models based in part on those of Livescu and Glass [20], but use discriminative classifiers of feature values to provide either observations or virtual evidence (VE) to the DBNs. In a previous work [34], we described an approach in which each visual frame is independently labeled with a set of classifiers, and showed a benefit of AF classifiers over viseme classifiers at various levels of visual noise. In this paper, we show the benefit of AF-based models in a medium-vocabulary word ranking task and in a small-vocabulary isolated phrase recognition task. Preliminary versions of some of the experiments in this paper have been reported previously [35], [36]. In this paper, we propose a class of models that unify those of [35], [36] and present additional experiments with improved results. Furthermore, we explore the use of dictionary-based models, in which words are broken into predefined subword units, versus whole-word (or, in our case, whole-phrase) models. We also explore the choice of observation model, i.e., the distribution of the visual signal given the hidden state.

2 BACKGROUND

2.1 Visual Speech Recognition

Automatic visual speech recognition has been studied for over 20 years, both as a stand-alone task and as part of audiovisual systems. The main research issues are visual observation design, the choice of speech units, and decoding, i.e., mapping the sequence of observation vectors to speech units. A comprehensive review can be found in [32].

Visual observations can be categorized as either appearance-based, model-based, or a combination of the two (for an overview, see [32]). Appearance-based observations are based on the intensity and color information in a region of interest (usually the mouth and chin area). The dimensionality of the raw observation vector is often reduced using a linear transform. In contrast, model-based methods assume a top-down model of what is relevant for recognition, such as the lip contours. The parameters of the model fitted to the image are used as visual observations.

The most common decoding model for VSR is the HMM. Several multistream models have been applied to speech processing in recent years [11], [27], [28]. To our knowledge, we are the first to develop multistream DBNs for visual-only data streams.

Although most HMMs/DBNs use a Gaussian mixture model for the state-dependent distributions, several discriminative classification methods have been used, including distance in feature space [30], neural networks [23], and support vector machines (SVMs) [10]. In [10], one SVM was trained to recognize each viseme, and its output was converted to a posterior probability using a sigmoidal mapping [31]. In this work, we use SVMs to classify articulatory features in the video stream and use their outputs as observations in the DBN.
For recognition of continuous word strings, additional Gaussians. This serves as our baseline for whole-word recognition and its distribution is most frequently modeled as a mixture of last. The variable \( s \) is the subword state; for a word with \( n \) phonemes, a typical choice is to allocate \( n \) separate HMMs for each word, which we refer to as a “whole-word” model. The variable \( s \) is the subword state, identical to the standard (nonarticulatory) approach to speech recognition.

A smaller number of research efforts have been aimed at explicitly modeling the states of articulators, allowing them to stray from their target values or desynchronize [9], [20], [33]. More recently, the use of articulatory knowledge has also been proposed (though not implemented) for visual speech recognition [26]. This is not a straightforward application of acoustic speech recognition techniques because, unlike the acoustic signal, the visual signal provides direct evidence for certain articulatory gestures (e.g., lip closing) that are ambiguous in the acoustic signal.

2.2 Articulatory Feature-Based Models in Speech Recognition

Articulatory models are an active area of work in automatic speech recognition (a survey can be found in [15]). Most of the work focuses on classifying articulatory feature values from the acoustic signal (e.g., [16], [17]). In this work, the classifier outputs are typically combined into either a phonetic likelihood (e.g., [17]) or a feature vector to be modeled with a Gaussian mixture distribution (e.g., [5]). These likelihoods or feature vectors are then used in a model in which each word or sub-word unit (e.g., a phoneme) is modeled as a hidden Markov model, identical to the standard model in which each word or sub-word unit (e.g., a phoneme) is represented with an HMM (typically with three states per phoneme/viseme). Observation models are shared among words with identical subword states. Fig. 4 shows such a model, which we refer to as a “dictionary-based” model. Here, \( p \) refers to the state within the phoneme-specific HMM, which is typically deterministic given the subword state \( s \) (unless the word has multiple pronunciations). Nodes with thick outlines denote variables that are deterministic given their parents. Now, at time \( t + 1 \) depends on \( p \) at time \( t \) since the transition probabilities are phoneme-dependent. The subword state \( s \) still encodes sequencing information (e.g., “first phone state in the word Bob”), while \( p \) encodes the actual phonetic unit (e.g., [b]).

Instead of a generative observation model, a discriminative phoneme or viseme classifier may be used. In this case, the DBN is identical except that the observation variable is replaced with a “virtual evidence” (or “soft evidence”) node [1], [29], corresponding to a scaled likelihood estimate derived from postprocessed classifier outputs. For acoustic speech recognition, this is most often done using multilayer perceptron classifiers [23] (here we use support vector machines).

Thus far, we have described several single-stream models—whole-word, dictionary-based, and dictionary-based with virtual evidence—that serve as baseline, viseme-based recognizers. We next describe the proposed articulatory models. Both the baseline and proposed models can be trained via expectation-maximization (EM) [8], as is standard in speech recognition, and decoding (testing) can be done using standard DBN inference algorithms [3].

3 Proposed Approach

In the multistream models we propose, each articulatory feature is associated with a separate sequence of hidden states. We allow for possible differences between the target and actual positions of the articulators, as well as for possible asynchrony between the state sequences. The proposed class of models is an extension of the approach of [20], which introduced a general model of pronunciation variation using articulatory variables. We extend...
these models to the task of lipreading, including lipreading-specific articulatory features and observation models based on the outputs of articulatory classifiers.

We consider two ways of incorporating the outputs of articulatory feature classifiers. Classifier outputs may not match the values in the dictionary, for example, the target articulation may involve closed lips, but in the actual production, the lips may only be narrowed. We experiment with two ways to handle this discrepancy: 1) by explicitly modeling the distribution of actual given target articulation, treating the (postprocessed) classifier outputs as “virtual evidence” (see below) and 2) by modeling the distribution of classifier outputs conditioned directly on the state (a generative model). We also consider both “dictionary-based” and “whole-word” models, as described in Section 2.3. In dictionary-based models, we explicitly map the current subword state to the intended articulation and share observation models among words with identical subword states. Dictionary-based models may use either the generative or VE-based observation models described above. For whole-word models, only generative observation models can be used since we do not have classifiers for each possible subword state.

In the following sections, we present: the sets of articulatory features we use for visual recognition, support vector machine-based classifiers of these features, and a more formal description of our models in terms of dynamic Bayesian networks.

3.1 Articulatory Feature Sets

Various articulatory feature sets have been proposed for acoustic speech recognition. In dealing with the visual modality, we limit ourselves to modeling the visible articulators. As a start, we choose a feature set based on the one in [20]. Specifically, we use features associated with the lips, since they are always visible in the image. The features are: lip opening (LO, with values closed, narrow, medium, and wide), lip rounding (LR, with values yes, no), and the labiodental feature, corresponding to an /f/ or /v/ articulation (LD, with values yes, no). This ignores other articulators that might be discernible from the video, such as the tongue and teeth. We will later show that adding a fourth feature associated with the teeth can improve the three-feature model.

We do not, in general, have access to ground-truth articulatory feature labels for training data; obtaining them would require tracking the state of the vocal tract, which is very challenging. In the experimental section, we compare two ways of obtaining labels: manually, using a human labeler, and automatically, by mapping phoneme labels to feature values. (Phoneme labels, in turn, can be obtained automatically through forced alignment with the known transcription.) Some combinations of feature values can occur with manual labeling but not with automatic labeling, e.g., {LO = narrow, LR = yes, and LD = yes}, if a speaker strays from the target articulation. Manual labels tend to be more consistent and, as we will show, produce better classifiers.

3.2 Articulatory Feature Classifiers

We convert the images to a sequence of appearance-based observation vectors, and classify each feature separately in each frame of the sequence using an SVM classifier. The DBN models require an estimate of the distribution of observations given each possible state of each articulatory feature, i.e., the likelihood.

We propose two ways of estimating the observation distributions. The first is to convert the output of each SVM to a probability. Given an observation vector \( x \in \mathbb{R}^n \) and the unthresholded, raw decision value of a binary SVM \( f(x) \), Platt [31] proposed to fit a sigmoidal function that maps from \( f(x) \) to an estimate of the posterior probability of the positive class:

\[
P(Y = 1|X = x) = \left(1 + e^{a(f(x) + b)}\right)^{-1},
\]

where \( a, b \) are the estimates using maximum likelihood. We use the multiclass extension of Platt’s method described in [6] to produce posterior probabilities over all values of a feature \( F, P(F = f|X = x) \) and map the posteriors to (scaled) likelihoods using

\[
P(X = x|F = f) \propto P(F = f|X = x)/P(F = f).
\]

The scaled likelihoods are used as virtual evidence in the DBN (see Section 3.3).

The second method we consider is to use the decision value \( f(x) \) directly as an observation. This can also be viewed as a nonlinear transform method for extracting visual observations.

We next describe the DBN-based models used to recognize words or phrases given the outputs of the articulatory classifiers.

3.3 Dictionary Models

Fig. 5 shows the DBN for one word in a dictionary-based articulatory model, using an observation model based on virtual evidence from AF classifiers. This model uses the three articulatory features described previously: LR, LO, and LD. However, the structure can be straightforwardly generalized to an arbitrary set of articulators. The variables in the model are as follows:

- \( s_{LR}, s_{LO}, s_{LD} \): The subword state corresponding to each articulatory feature, analogously to \( s \) in Fig. 4.
- \( p_{LR}, p_{LO}, p_{LD} \): The phonetic state corresponding to the current subword state for each articulator, analogously to \( p \) in Fig. 4.
- \( f_{LR}, f_{LO}, f_{LD} \): The value of each feature, with distribution given by \( p(f|p) \).
- \( v_{LR}, v_{LO}, v_{LD} \): Virtual evidence provided by classifiers for LR, LO, and LD. The distribution \( p(v|f) \) is the postprocessed output of the classifier for feature \( F \) (see Section 3.2).
- \( a_{F_i - F_j} \): These variables encode the asynchrony constraints. We define the degree of asynchrony between any two features \( F_i \) and \( F_j \) as \( |a_{F_i - F_j}| \). The variable \( a_{F_i - F_j} \) takes on values in \( \{0, 1, 2, \ldots, m\} \), where \( m \) is the maximum state index in the current word. The distribution \( p(a_{F_i - F_j}) \) is the probability of the two features \( F_i \) and \( F_j \) desynchronizing by \( a_{F_i - F_j} \) states.
• $c_{F_i,F_j}$: These binary variables, always observed with value 1, enforce the asynchrony constraints. The observed value is allowed only if $|x_{F_i} - x_{F_j}| = a_{F_i,F_j}$.\footnote{We note that the structure could be simplified somewhat, as in \cite{19}, replacing $a_{F_i,F_j}$ and $c_{F_i,F_j}$ with a single variable; however, this simpler structure does not allow learning of the asynchrony probabilities via a straightforward application of expectation-maximization.}

We note that the virtual evidence variables in this model can also be replaced with observation vectors modeled with a Gaussian mixture distribution, analogously to the single-stream model of Fig. 4. We compare these variants in Section 5.3.

### 3.4 Dictionary Models Using Viseme Classifiers

The previous section described an articulatory feature-based dictionary model in which the evidence is provided by AF classifiers. It is also possible to combine an AF-based pronunciation model with viseme classifiers, by replacing the multiple variables $v_{LR}, v_{LO}, v_{LD}$ with a single-viseme virtual evidence variable $v_{VIS}$, whose parents are $f_{LR}, f_{LO}, f_{LD}$. In such a model, the viseme classifier output is converted to virtual evidence $p(v_{VIS}|f_{LR}, f_{LO}, f_{LD})$ using a (many-to-one) mapping from features to visemes. If the streams in this model are constrained to be synchronous ($P(a_{F_1,F_2} = n) = 0$ for all $n > 0$), then it is equivalent to a baseline single-stream model, except that it has multiple (identical) transition probabilities.

### 3.5 Whole-Word/Small-Vocabulary Models

Analogously to the single-stream case, articulatory models may be dictionary-based or whole-word. Fig. 6 shows the DBN for a word in a whole-word recognizer. The structure is similar to that of the dictionary-based model of Section 3.3, but there are no explicit variables for the phonetic or articulatory state. For this reason, the outputs of the articulatory classifiers cannot be used directly as virtual evidence in this model. Instead, the classifier outputs are used as observations, $a_F$ for each feature $F$, and the observation distribution $p(a_F|s_F)$ is modeled as a mixture of Gaussians. The advantage of a whole-word model is that it is not necessary to craft the DBN. As is common in speech recognition, we use an exponential weight $\lambda$ on the observation models. For example, in the model of Fig. 5, we use $p(v_{F}|f_{F})^\lambda$ instead of $p(v_{F}|f_{F})$ for each feature $F$. In the experiments, $\lambda$ is tuned only for the baseline models, and the remaining models use the same $\lambda$; this gives an advantage to the baselines, but the AF-based models still outperform them. We also note that the results were roughly constant over a large range of $\lambda$ in each experiment.

### 4 EXPERIMENTAL DETAILS

We perform two sets of experiments using two audiovisual data sets of American English speech. The first set of experiments (Sections 5.1 and 5.2) is a medium-vocabulary word ranking task (with 1,793 words) and uses a subset of an existing corpus of read phrases, and the second (Section 5.3) applies dictionary and whole-word models to the more practical scenario of short-phrase recognition (using SMALL-V). All of the experiments follow the outline given in Algorithm 1.

The main goals of the experiments are: 1) to compare the effects of using AF-based versus viseme-based observation models (classifiers) and 2) to compare the effects of using synchronous versus asynchronous pronunciation models (DBNs), independent of which classifiers are used. A synchronous pronunciation model is the special case of our models in which the features are constrained to be completely synchronous (i.e., $a_{F_1,F_2} = 0$). Using viseme classifiers with a synchronous pronunciation model results in a model almost identical to the conventional viseme-based HMM that has been used previously for VSR (e.g., \cite{10}) and we consider this our baseline model.
Algorithm 1. Overview of experimental approach

**Input**: A video stream of a speaker’s face

**Initialization**: estimate parameters of SVM AF classifiers and DBN models on training data.

1. Detect the face and track the mouth region.
2. Extract visual observations from each frame.
3. Classify AFs in each frame using a bank of SVMs.
4. Postprocess SVM outputs for use as observations in DBN.
5. For each word or phrase \( w \), compute posterior probability of \( w \) using inference on corresponding DBN.

5.1 Single-Speaker Experiments on MED-V

To investigate how sensitive our models are to the quality of the training labels, we have manually labeled the 21 utterances read by one speaker (Speaker “03”). We compare models using manual labels to models using a mapping from phonemes to canonic feature values (see Section 3.1). The mapping used for canonic labels is shown in the Appendix. Fig. 2 shows the mean image for each feature value, reconstructed from its PCA coefficients.

### 5.1.1 Classifiers

We first compare the behavior of classifiers (of both features and visemes) trained on automatic and manual labels. The data is split into a training set of 10 utterances and a test set of 11 utterances. For the viseme classifier, there are six classes, consisting of those combinations of feature values that occur in the automatically labeled training set. When mapping manual AF labels to viseme labels, we use the same set of visemes as in the canonic labels, even though there are some combinations that are not allowed in the canonic mapping.

We note that classifier accuracy measures are of limited utility; the true test is recognition performance using each set of classifiers, which we discuss in the next section. It is nevertheless useful to understand the behavior of the classifiers. Table 1 shows the raw classifier accuracies, (the percentage of frames classified correctly), as well as the average per-class accuracies (the percentage of correctly classified frames for each class, averaged over the \( N \) classes). Chance performance is given in parentheses (\( \frac{1}{N} \) for per-class accuracy: the percentage of training frames corresponding to the most frequent label for raw accuracy). In these results, the correct labels are taken to be manual labels for the manual-train classifiers and automatic labels for the automatic-train classifiers. What we are testing is, therefore, the “learnability” of each labeling by this type of classifier.

We hypothesize that the canonic labels are less consistent or “noisier” and, therefore, expect lower accuracies from the automatic-train classifiers. This is, indeed, what we find: The manual-train classifiers have higher accuracies than the corresponding automatic-train ones, in most cases, by a wide margin. The two cases in which the manual-train classifiers have lower accuracies—the raw accuracies of the LO and viseme classifiers—correspond to much lower chance performance (and therefore, a more difficult task) for the manual labels. The LD classifier’s per-class accuracy almost doubles, when manual labels are used, from chance to 93 percent. The poor performance of the automatic-train LD classifier is most likely due to the noisiness of the canonic labels, which often miss the appearance of labiodental closure. Note that the raw accuracies are not very informative in this case since the more frequent label, \( no \), occurs 99 percent of the time.

Overall, the classifier performance results demonstrate that, as expected, the manual labels are more easily learned by the SVM classifiers. In the following section, we show that there are also large differences in recognizer performance.

### 5.1.2 Word Ranking Results

Here, the task is to recognize isolated words excised from continuous speech, an extremely difficult lipreading task even for humans. The overall error rate is, therefore, not a meaningful performance metric. Instead, we perform a word-ranking experiment. For each sequence in the test set, we compute the probability of each word in the vocabulary and rank the words based on their relative probabilities. Our goal is to obtain as high a rank as possible for the correct word (where the highest rank is 1 and the lowest 1,793). We evaluate performance by the mean rank of the correct word (see [35] for distributions of correct word ranks). Since the vocabulary is too large to learn a separate model for each word, we use dictionary-based models for this task (Fig. 5).

We compare the effects of the following on the word ranking results: viseme versus AF classifiers, synchronous versus asynchronous training, and the quality of the training labels. The results are shown in Table 1. We note that it is arguable what the ground-truth labels should be: If manual labels are used, it may not be a fair test of the automatic-label classifiers, and vice versa. The use of both labelings does not test true correctness, but does test the consistency of the labels.

---

**Table 1**

<table>
<thead>
<tr>
<th>Labels</th>
<th>LO</th>
<th>LR</th>
<th>LD</th>
<th>Viseme</th>
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<tbody>
<tr>
<td>per-class acc.</td>
<td>automatic</td>
<td>44 (25)</td>
<td>64 (50)</td>
<td>49 (50)</td>
</tr>
<tr>
<td></td>
<td>manual</td>
<td>59 (25)</td>
<td>81 (50)</td>
<td>93 (50)</td>
</tr>
<tr>
<td>raw acc.</td>
<td>automatic</td>
<td>86 (87)</td>
<td>84 (84)</td>
<td>98 (99)</td>
</tr>
<tr>
<td></td>
<td>manual</td>
<td>83 (69)</td>
<td>89 (78)</td>
<td>99 (99)</td>
</tr>
</tbody>
</table>

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2. We could add these combinations as extra viseme classes; however, they occur extremely rarely and would have insufficient training data. (This is, of course, one of the motivations for using articulatory features.)

3. We note that it is arguable what the ground-truth labels should be: If manual labels are used, it may not be a fair test of the automatic-label classifiers, and vice versa. The use of both labelings does not test true correctness, but does test the consistency of the labels.
TABLE 2
Mean Rank of the Correct Word for Several Recognizers on Speaker 03 from the MED-V Corpus

<table>
<thead>
<tr>
<th>Classifier (mapping)</th>
<th>Mean rank, sync model</th>
<th>Mean rank, async model</th>
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<tr>
<td>Viseme (canonic)</td>
<td>232.8*</td>
<td>216.3 (0.2)</td>
</tr>
<tr>
<td>Feature (canonic)</td>
<td>232.7 (0.5)</td>
<td>200.1 (0.1)</td>
</tr>
<tr>
<td>Viseme (manual)</td>
<td>232.6*</td>
<td>225.8 (0.3)</td>
</tr>
<tr>
<td>Feature (manual)</td>
<td>135.8 (4e-05)</td>
<td>125.6 (5e-05)</td>
</tr>
<tr>
<td>Feature (oracle classifiers)</td>
<td>113.0 (4e-04)</td>
<td>109.7 (4e-04)</td>
</tr>
</tbody>
</table>

Numbers in parentheses are p-values relative to viseme baselines (marked *).

5.2 Multiple-Speaker Experiments on MED-V

Since we can easily produce automatic feature labels for more than one speaker, in this section, we perform canonic-label experiments on multiple speakers from MED-V. The experimental setup is identical to the canonic-label experiments in Section 5.1, except that the classifiers are trained on multiple speakers and the DBN parameters are learned from data. We perform word ranking experiments on the eight speakers, all of which read the same set of sentences.

5.2.1 Classifiers

For each speaker, we use the even-numbered utterances for training and the odd-numbered utterances for testing. Fig. 7 shows the per-class accuracies for the LO, LR, LF, and VIS classifiers. It is clear that, for speakers 00, 01, 02, 03, and 07, the classifiers perform very poorly, sometimes at chance levels. For the other five speakers, accuracy is quite good. Speakers in the former group have some tracking problems, especially 01 and 07, for which classification rates are the lowest and near chance. We exclude these two speakers from the following experiments, using the remaining eight. Sample tracking results for all 10 speakers are shown in the Appendix, which can be found in the Computer Society Digital Library at http://doi.ieeecomputersociety.org/10.1109/TPAMI.2008.303.

5.2.2 Word Ranking Results

We performed word ranking experiments on the eight speakers 00, 02, 03, 04, 05, 06, 08, and 09, using the same procedure as in Section 5.1.2. We find small but not statistically significant improvements for the proposed models. Over all words in the test set, the mean rank of the correct word is 123.3 using the baseline model (synchronous pronunciation model, viseme-based observation model). Switching to an asynchronous pronunciation model produces a mean rank of 121.5, a synchronous model with a feature-based observation model gives 119.0, and an asynchronous model with a feature-based observation model gives 118.5.

The three speakers with poorer classifier performance (00, 02, and 03) also have significantly worse ranking performance. If we consider only the speakers with average classification accuracy > 50 percent (speakers 04, 05, 06, 08, and 09), there is a statistically significant improvement in mean rank from using feature-based over viseme-based models (from 64.6 to 52.1, p-value 0.02), but not from using asynchronous models (from 64.6 to 66.2 for viseme-based models, 52.1 to 52.5 for feature-based models). On the speakers with poor classifiers (00, 02, and 03), feature classifiers do not help over viseme classifiers (from 210.5 to 218.4); asynchronous models improve over synchronous ones (210.5 -- >203.7, 218.4 -- >216.7), but not significantly so. We conclude that allowing asynchrony on this task does not make a statistically significant difference overall, perhaps because the labels were mapped from inherently synchronous phoneme labels. However, when the classifiers perform reasonably, AF-based models significantly outperform viseme-based ones.

4. The mean ranks are better than in earlier work [35] due to improvements to the classifiers.
5.3 Phrase Recognition Experiments on SMALL-V

The word ranking experiments have shown that articulatory feature-based models have an advantage over conventional viseme-based ones, at least when the classifiers perform reasonably. Next, we investigate whether this advantage applies in the more practical setting of the small-vocabulary command-and-control recognition task of the SMALL-V data set. Since the vocabulary is small, we consider both dictionary and whole-word models. We also compare Gaussian observation models with the VE-based models used thus far. In addition, we experiment with adding a fourth articulatory feature (which is, in principle, not needed to distinguish the phrases). Finally, we compare our models against another baseline, which uses linear transform image features directly as observations.

5.3.1 Classifiers

In these experiments, we use only manual AF and viseme labels. A subset of the frames in the classifier training set was labeled manually with AF values. We train AF and viseme SVM classifiers, now using a one-versus-all strategy for multiclass SVMs, with six SVMs trained for the three AFs (four for LO, one for LR, and one for LD) and six SVMs for the six visemes. The average per-class accuracies of the classifiers on the test set are 79 percent for LO, 78 percent for LR, 57 percent for LD, and 63 percent for visemes.

5.3.2 Adding a New Feature

The feature set so far has included three features associated with the lips. Although these are sufficient to differentiate between the test phrases, we now add a fourth AF describing the position of the teeth (TP), with three values: open (used when there is a space between the teeth), neutral (used when there is no visible space), and unknown (used when the teeth are not visible). To determine whether using more features than the minimum needed to distinguish the vocabulary improves performance, we conduct experiments with both the original three-feature set and the new four-feature set. To make for a fair comparison between AF-based and viseme-based models, we also expand the viseme set to eight, corresponding to those combinations of AF values that occur in the training data.

5.3.3 Recognition Results

Table 3 summarizes the phrase recognition accuracies. Recall that each phrase was recorded three times; each recognition experiment is conducted three times, training on two repetitions of each phrase and testing on the remaining repetition. The table shows the average accuracies over the three trials.

<table>
<thead>
<tr>
<th></th>
<th>dictionary</th>
<th>whole-word</th>
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<tbody>
<tr>
<td>6V +VE</td>
<td>31</td>
<td>43</td>
</tr>
<tr>
<td>3AF</td>
<td>69</td>
<td>52</td>
</tr>
<tr>
<td>3AF</td>
<td>58</td>
<td>64</td>
</tr>
<tr>
<td>LO 8V sync</td>
<td>78</td>
<td>79</td>
</tr>
<tr>
<td>LO 3AF sync</td>
<td>4 AF sync</td>
<td></td>
</tr>
<tr>
<td>LO 4 AF sync</td>
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</tr>
</tbody>
</table>

The right side of the table, under “whole-word,” gives results for three baseline models: “6V,” the viseme baseline corresponding to the 3-AF model; “8V,” the viseme baseline for the 4-AF model; and “PCA,” an HMM-based model with Gaussian observation distributions over raw PCA visual features (with the number of PCA coefficients set at 5 by cross-validation on the training data). Of these, the “PCA” baseline has the best performance. Comparing the 3-AF synchronous model to its 6-viseme equivalent, and the 4-AF synchronous model to its 8-viseme equivalent, we again find that feature-based models outperform viseme-based ones.

The “3-AF” and “sync+3AF” columns show that AF-based models with the original 3-feature set outperform either viseme-based baseline, but not the PCA baseline. This is not surprising since the three lip features presumably carry less information than the full image on which the PCA coefficients are based. However, the “4-AF” column shows that, with four features, the AF-based model outperforms the PCA baseline. Finally, the last column gives the performance of an asynchronous 4-AF model, in which three pairs of streams were allowed to desynchronize by up to one state—LO and LR, LO and LD, and LO and TP. This model achieves the best overall performance, although the difference between it and the synchronous version is not statistically significant on this data set. Adding the fourth feature (TP) improved the accuracy of the synchronous DBN from 64 percent to 78 percent, and of the asynchronous DBN from 66 percent to 79 percent. Note that the four AFs arguably still do not capture all of the relevant information in the image; for example, some aspects of tongue motion may be visible and independently informative.

6 Conclusion

We have presented a class of models that use multiple streams of articulatory features to model visual speech. This paper unifies previously presented work [35], [36] and includes additional model and experimental variants. In our approach, dynamic Bayesian networks are used to represent streams of hidden articulator states and to allow for asynchrony between them. A bank of support vector machine classifiers provides input to the DBN, in the form of either virtual evidence (probabilities) or raw margin outputs. We have presented experiments conducted on two visual speech tasks, a medium-vocabulary word-ranking task and a small-vocabulary phrase recognition task. The main findings are: 1) AF-based models outperform conventional single-stream viseme-based models on both tasks and 2) models allowing for asynchrony between streams usually outperform synchronous models, but not at a statistically significant level on our data. One reason for the improved performance with AF-based models may be that some visemes occur infrequently and, thus, have too little training data, while AF classifiers can utilize training data more efficiently. It is also possible that there are too many classes in the viseme-based multiclass SVMs, suggesting that investigations with alternative, inherently multiclass, classifiers may be useful.

A few additional aspects of the results are noteworthy and suggest possible directions for future work. We have found that, although not always visible in the image, articulators other than the lips can provide important information and help to improve performance (Section 5.3.3). Additional features, such as tongue position, may improve performance even further. We have also found (in Section 5.2) that classifier (and, therefore, recognition) performance varies widely across speakers; one area for future work is, therefore, the investigation of the causes of this variability. The word-ranking experiments with manual labels for a single speaker (Section 5.1.2) have underscored the importance of accurate training labels. Manually labeling large data sets may

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<td>3AF +4AF</td>
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<td>6V 8V</td>
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not be feasible, but future work may include an iterative procedure to refine the automatic labels.

Finally, two important directions for future work are the application of the proposed models to more casual (conversational) speech styles and the addition of acoustic modality. The degree of asynchrony between articulators may be more pronounced in conversational speech and the types of models we have used were originally motivated by conversational speech phenomena [19]. In the case where we include the acoustic modality, our models allow the combination of audio and visual speech to be done at the articulatory feature level, as opposed to the phoneme/viseme level. Preliminary work in this direction has recently begun [12], [21]. We believe this may be a more appropriate model for audio-video fusion, since it accounts for the apparent asynchrony among the acoustic and visual signals [11] naturally via the mechanism of asynchronous AF streams.

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REFERENCES