

Combination of Multiple Acoustic Models with Multi-scale Features for Myanmar Speech Recognition

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Abstract

We proposed an approach to build a robust automatic speech recognizer using deep convolutional neural networks (CNNs). Deep CNNs have achieved a great success in acoustic modelling for automatic speech recognition due to its ability of reducing spectral variations and modelling spectral correlations in the input features. In most of the acoustic modelling using CNN, a fixed windowed feature patch corresponding to a target label (e.g., senone or phone) was used as input to the CNN. Considering different target labels may correspond to different time scales, multiple acoustic models were trained with different acoustic feature scales. Due to auxiliary information learned from different temporal scales could help in classification, multi-CNN acoustic models were combined based on a Recognizer Output Voting Error Reduction (ROVER) algorithm for final speech recognition experiments. The experiments were conducted on a Myanmar large vocabulary continuous speech recognition (LVCSR) task. Our results showed that integration of temporal multi-scale features in model training achieved a 4.32% relative word error rate (WER) reduction over the best individual system on one temporal scale feature.

Keywords: acoustic modelling; deep convolutional neural networks; multi-scale features; Myanmar speech recognition; ROVER combination.

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1. Introduction

Automatic speech recognition (ASR) technique is widely used for transcribing audio speech to text. Due to the strong power of modelling ability on temporal sequence, the hidden Markov model (HMM) has been intensively used in ASR systems. With Gaussian mixture model (GMM) [13, 14] for feature statistic distribution estimation, the GMM-HMM framework has dominated the ASR field for several decades. In a hybrid HMM with deep neural network (DNN-HMM) framework, DNNs have been proposed to replace GMMs to compute state observation probabilities for all tied states in HMM and have achieved a large gain in many challenging ASR tasks [6, 7, 8, 17, 21]. Compared to GMM-HMM, the hybrid DNN-HMM can easily capture highly correlated feature inputs under several consecutive speech frames within a relatively large context window, where GMM can handle only one frame each time. Recently, convolutional neural networks (CNNs) have been attracting much attention for acoustic models [18, 23, 24] because CNNs are able to explore local invariant and hierarchical features in acoustic speech that DNNs cannot explore.

CNN attempts to capture structural locality in the feature space by applying convolutional filters. The extracted feature is supposed to improve the classification performance. As we know, the target labels (e.g., senones or phones) may have different temporal durations, i.e., the label category exists in different temporal scales. For example, for stop phones the duration may be less than 30 milliseconds while for vowels the duration may be more than 300 milliseconds. However, in most acoustic modelling using CNN, a fixed windowed input feature of several frames corresponding to a target label is used in model training. If different temporal scale of input feature is used for different target label training, the performance for ASR is supposed to be improved. In this work, we focus on whether combination of temporal multi-scale features in model training can improve the performance or not.

Combining information at multi-scales (either temporal or spatial) recently obtained great success in traffic sign recognition [20], semantic segmentation [11] and depth map prediction [3]. To deal with the numerous variations in acoustic space, it is possible to combine multiple acoustic models trained either with different acoustic features or different model architectures using ensemble model combination techniques [1, 2, 10, 26]. All these techniques can leverage all structural information potentially available and increase the robustness of the overall system. In this study, we introduced and evaluated a Myanmar ASR system with effective integration of temporal multi-scale features. For a feature type from one temporal scale, a deep CNN acoustic model was built. Models with different feature scales were combined in a Recognizer Output Voting Error Reduction (ROVER) process on the N-best hypothesis lists during speech recognition.

Since 2015, we have built the first Myanmar LVCSR system [9] based on DNN-HMM acoustic model framework. And later, a CNN-HMM baseline system has been built on the same task. The integration of temporal multi-scale features in acoustic modelling is based on our CNN-HMM baseline. In the next section, we discuss the basic structure and concepts of convolutional neural network. Section 3 introduces the basic architecture of our system and describes the detailed components in our proposed model. Experiments and results are presented in Section 4. Conclusions are given in Section 5.

2. Convolutional neural network

In speech recognition, deep convolutional neural networks consist of one or more convolutional layers followed by pooling process, then on top of these CNN layers, one or several fully connected layers are stacked for further feature processing and a softmax layer is stacked at last to output a normalized probability for acoustic classification. Compared with DNNs, deep CNN restricts the network architecture with local connections and weight sharing in the input layer so that it can explore local correlations in feature processing.

A convolutional layer does the convolutions on feature maps of the previous layer using filters, and then adds a bias scalar to the corresponding feature map, followed by a non-linear operation [25]. Feature maps are the basic units of convolutional and pooling layers.

In the typical speech inputs, the size of feature map can be represented as $\#times \times \#feadim$, where $\#times$ is the context window size of the input features and $\#feadim$ is the dimension of features (e.g., 38 dimensions Mel-frequency cepstral coefficient (MFCC) is used in this work). Therefore, one way to extract multi-scale features is to feed multiple input sizes by varying the context window sizes. Another way to extract multi-scale features is by using filters with different sizes because filters in convolutional layers can be used as feature extractor to capture time-frequency spectral variations.

The purpose of convolution is to extract features from input feature map using filter, where both the feature map and the filter can be represented as matrices.

During convolution operation, the filter moves along the two dimensions of input feature and computes the dot product to output a new feature map as:

$$\mathbf{h}^{(\ell)} = \sigma(\mathbf{W}^{(\ell)} * \mathbf{h}^{(\ell-1)} + \mathbf{b}^{(\ell)}) \quad (1)$$

Equation (1) shows the simplest situation where only one feature map exists in the previous layer, where $\mathbf{h}^{(\ell-1)}$ and $\mathbf{h}^{(\ell)}$ are feature maps in two consecutive layers. The convolution operation (denoted as $*$) is performed within the filter $\mathbf{W}^{(\ell)}$ and the feature map $\mathbf{h}^{(\ell-1)}$.

The bias $\mathbf{b}^{(\ell)}$ is added and finally the activation function $\sigma(\cdot)$, typically sigmoid or ReLU will be applied to generate the outputs of the convolutional layer. When multiple feature maps are presented in the previous layer, the results of convolution operations are accumulated first before adding the bias. The pooling layer performs down-sampling on the feature maps of the previous layer and generates new ones with a reduced resolution. In this work, max-pooling was used in all CNN layers. The max pooling operation involves picking up the maximum from adjacent filter outputs. The extracted features are finally processed by fully connected layers.

3. Temporal multi-scale deep CNN acoustic models and combination

The basic architecture used in this work is illustrated in Fig. 1. There are two main parts: building multiple deep CNN based ASRs and model combination. First, multiple ASRs are built based on acoustic models trained with

different feature scales.

The outputs of all ASRs which provide complementary information sources for speech recognition are then combined in a ROVER process on the N-best hypothesis lists to improve the performance of the whole system.

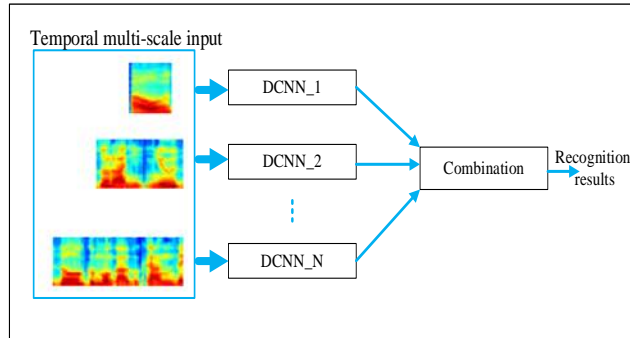


Figure 1: Design of the proposed temporal multi-scale features based deep CNN speech recognition system

3.1. Acoustic model architecture

The proposed system is a combination of several deep CNNs acoustic models that share the same base architecture and are trained on the same data in the same training procedure, but differ in their input feature scales and filter sizes of the first convolutional layer. The base architecture of deep CNN is designed as shown in Fig. 2. Our base architecture consisted three convolutional layers, followed by one pooling layer, three fully connected layers and a softmax output layer. The third convolutional layer took the form of Network in Network (NIN) structure [16].

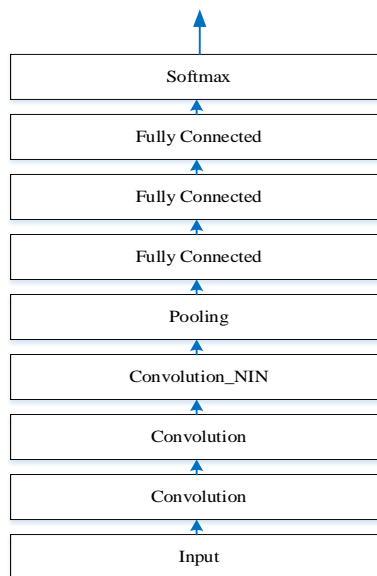


Figure 2: Architecture of deep CNN acoustic modelling

3.2. Decoding with language model

As shown in Fig. 1, the combination module is a ROVER process on the N-best hypothesis lists from the decoding process of all models corresponding to different temporal scales. The decoding process for each model is shown in Fig. 3. Decoding is the process to calculate which sequence of words is most likely to match to the acoustic signal represented by the feature vectors. Initially, features were extracted from the recorded speech signal as MFCCs. Decoding was then performed with an acoustic model, a pronunciation lexicon and a language model. The lexicon is a list of words together with their corresponding phone sequence. Language model (LM) is a fundamental component in ASR system. To perform optimally, a LM should be trained from the same domain as the content that it will be applied to. The speech decoding is done with a weighted finite state transducer (WFST)-based decoder. In this work, NICT SprinTra decoder [19] was used for decoding. For each ASR, N-best hypothesis lists were extracted from the n-gram LM based lattices.

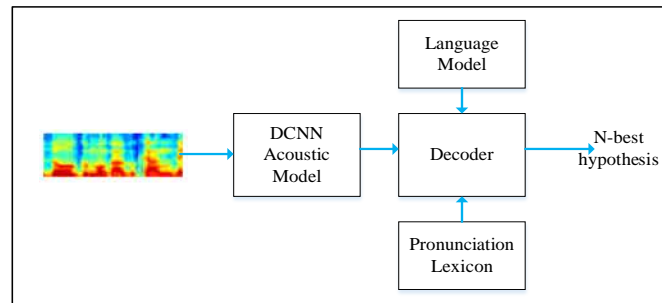


Figure 3: Decoding to generate N-best hypothesis for temporal scale based ASR system

3.3. Combination of outputs from different acoustic models

Combining outputs from ASR systems with different acoustic models helps to provide auxiliary information for improving speech recognition accuracy. ROVER was applied on the N-best lists generated from all ASRs. The system combination procedure of the used ROVER approach is described in Fig. 4. After the N-best hypotheses were obtained, the normalization was applied to scale the scores on the weighted N-best lists. After that, the N-best lists from each ASR were aligned into a single confusion network, as in [12]. Once the network was generated, a path with the lowest expected word error rate was extracted from all the N-best hypotheses with a voting search process. Additionally, the word posterior probability was calculated as the word confidence by summing the normalized scores for all N-best lists that contained the voted word.

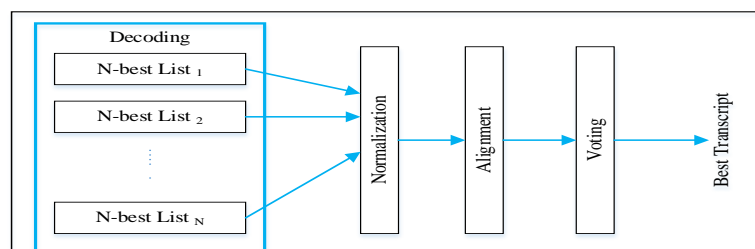


Figure 4: System combination procedure of N-best list-based ROVER

4. Experiments

The experiments were carried out on 452 hours of conversational speech, of which 438.5 hours were used as the training set and 13.5 hours were reserved as the validation set. The lexicon contains pronunciations for all words and word fragments in the training data. The n-gram language model (LM) was built using the modified Kneser-Ney smoothing method [22] with all training transcripts. The language model used in this task incorporates 236,171 words, as in lexicon. Evaluation was carried out on a 9.8 hours test dataset.

4.1. Feature extraction

Speech is recorded with a microphone with a sampling frequency of 16-kHz. Speech feature vectors are represented as the MFCC, which is popularly used in traditional GMM-HMM based framework for ASR. MFCC features were extracted using a 25-millisecond hamming window with 10 milliseconds frame rate. The input features consisted of MFCCs (12 cepstral coefficients without energy) along with their first and second order derivatives, in total 38 ($12 \times 3 = 36$ with another two dimensions of the first and second order derivations of log power energy).

4.2. Multi-scale deep CNNs acoustic models

Before training deep CNN-based (ASR_1 - ASR_8) acoustic models, a basic context dependent triphone HMM model with GMM based output probability was first trained to generate the senone alignments for later CNNs training. Following triphone training of the GMMs, model-space discriminative training was done using the boosted maximum mutual information (BMMI) criterion [5]. All models evaluated in this study used 3841 tied-tripphone states (senones), determined by context dependent GMM-HMM system. The baseline GMM-HMM model was built with Kaldi toolkit [4].

Based on the alignment from GMM-HMM model, the deep CNN based acoustic models were trained. The architecture of deep CNNs used in this work consisted of three convolutional layers, followed by one pooling layer, three fully connected layers and a softmax output layer. The input features used for all CNNs were 38 dimensions MFCC normalized with zero mean per speaker. The input layers were designed to process input features with temporal context windows of 3, 9, 11, 13, 19, 23, 27 and 31 frames, therefore, the input layers were with 114, 342, 418, 494, 722, 874, 1026 and 1178 dimensions for eight CNN acoustic models (denoted as ASR_1 to ASR_8), respectively. The first convolutional layer had 180 filters with filter sizes (3×6) for ASR_1 , (9×6) for ASR_2 , (11×6) for ASR_3 , (13×6) for ASR_4 , (19×6) for ASR_5 , (23×6) for ASR_6 , (27×6) for ASR_7 and (31×6) for ASR_8 , i.e., the receptive fields are with multi-temporal scales for the CNN. For all ASR s, the second and third CNN layers had 180 filters with filter size (1×6) and (1×1), respectively. The stride size was fixed to 1. A max-pooling process with pooling size of (1×2) was used in this work. All three fully connected layers had 1024 nodes in each which were used to further transform the features extracted from CNNs. Sigmoid function was used as the nonlinear activation function for hidden units. The softmax layer had 3841 output targets corresponding to the HMM tied states (senones) in GMM-HMM ASR framework.

All the deep CNN models were first trained with a criterion to minimize the frame-level cross-entropy (CE)

criterion, then a sequential discriminative training based on state level minimum Bayesian risk (sMBR) criterion was adopted to further improve the model [15]. In the training, the standard back-propagation algorithm with stochastic gradient descent based optimization was applied.

4.3. Evaluation criterion

The most common measure to evaluate the performance of a speech recognition system is word error rate (WER). The hypothesized transcript is aligned to the reference transcript on words through the method of dynamic programming. Three sets of errors are computed: substitution error (S) where a word is substituted by ASR to a different word, insertion error (I) where a word presents in the hypothesis but absents in the reference, deletion error (D) where a word presents in the reference but missing from the hypothesis. The accuracy (Acc) is defined as:

$$\text{Acc} = \frac{T - D - S - I}{T} \times 100\% \quad (2)$$

where T is the number of words in the correct transcription, D is the number of deleted words, S is the number of substituted words and I is the number of insertions. The error rate is closely related to the accuracy and calculated as:

$$\text{WER} = \frac{D + S + I}{T} \times 100\% = 100\% - \text{Acc} \quad (3)$$

4.4. Experimental results and discussion

We experimented with eight different models that differ mainly in the context window sizes and the filter sizes of the first convolutional layer. Out of the eight models built, only models given better performance in the final system combination are shown here.

Table 1: Results (WER%) of ASRs on the test set using CE and sMBR criteria

System	Context window	CE	sMBR
ASR ₃	11	41.50	31.59
ASR ₅	19	40.85	28.69
ASR ₆	23	40.45	28.76
ASR ₈	31	40.52	29.03

Table 1 compares the performance of our individual models using CE criterion and sMBR criterion. These results illustrated that training with sMBR criterion produced lower word error rate by roughly 10% over training with CE criterion for all acoustic model architectures, and models with different feature scales got different word error rates. Moreover, when we analyzed the accuracy of utterance by utterance on each scale, we

find that even the same utterance got different word error rates under different feature scales, as in Fig. 5.

Table 2: Results (WER%) of different system combinations

System	sys1	sys2	sys3
ASR ₃			○
ASR ₅	○	○	○
ASR ₆	○	○	○
ASR ₈		○	○
WER %	28.04	27.64	27.27

To show the effectiveness of combining ASRs, different combinations of ASRs after the ROVER process is listed in Table 2. From this table, we see that the combination of ASR₆ and ASR₅, the system (sys1) achieved 28.04%. Through a series of experiments, performance constantly improved from 28.04% to 27.27% in sys3. Therefore, the best ROVER combination was achieved 4.32% relative (1.42% absolute) word error rates reduction over the individual system on one temporal scale feature.

Reference transcript	ကြို့ဆို ပါတယ် ဂျပန် ကို အလည်အပတ် လာတာလား
ASR₆	ဟုတ်တယ် စု ပါတယ် ဂျပန် ကို အလည်အပတ် လာတာလား \$(ဟုတ်တယ်) \$\$ (ကြို့ဆို -> စု) ပါတယ် ဂျပန် ကို အလည်အပတ် လာတာလား Acc=66.67% [T=6, D=0, S=1, I=1]
ASR₅	ကြို့ဆို ပါတယ် ဂျပန် ကို လည်ပတ် လာတာလား ကြို့ဆို ပါတယ် ဂျပန် ကို \$\$ (အလည်အပတ် -> လည်ပတ်) လာတာလား Acc=83.33% [T=6, D=0, S=1, I=0]
ROVER	ကြို့ဆို ပါတယ် ဂျပန် ကို အလည်အပတ် လာတာလား Acc=100.00% [T=6, D=0, S=0, I=0]

Figure 5: Output transcripts of ASR₆, ASR₅ and ROVER over the same input utterance

Results in Fig. 5 demonstrate that the ROVER based combination clearly improve the decoding performance, even with just two multi-scale deep CNNs in the model combination. Given the same speech to recognize, ASR₆ and ASR₅ output very similar results but with errors such as insertion (I) and substitution (S) of incorrect words. Since the two ASRs are based on different feature scales, error segments across ASRs are uncorrelated. Therefore, it is possible to improve the speech recognition accuracy by combining ASRs. Ultimately, we can conclude from this experiment that each model has complementary information to achieving better performance.

5. Conclusions

In our study, we focus on using the complementary information from different deep CNNs acoustic models, which differ mainly in context window sizes and filter sizes, to Myanmar speech recognition. We have shown that models trained with temporal multi-scale features hold sufficient complementarity for successful model

combination and ROVER based combination was efficient for improving recognition accuracy. We achieved a 4.32 % relative word error rates reduction with the N-best list based ROVER process. For future research, we expect additional gains from using attention model which can learn to weight the multiple scales according to the input feature scales.

6. Recommendations

This work describes an approach to build a robust automatic speech recognizer that can be utilized for transcription of Myanmar audio speech to text.

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References

- [1] B. Hoffmeister, C. Plahl, P. Fritz, G. Heigold, J. Loof, R. Schluter, et al. "Development of the 2007 RWTH mandarin LVCSR system," In Proc. of IEEE 2007 Workshop on Automatic Speech Recognition and Understanding (ASRU), 2007.
- [2] C. Breslin and M.J. Gales. "Generating complementary systems for speech recognition," In Proc. INTERSPEECH, 2006.
- [3] D. Eigen, C. Puhrsch and R. Fergus. "Depth map prediction from a single image using a multi-scale deep network," In Proc. NIPS, 2014, pp. 2366–2374.
- [4] D. Povey, A. Ghoshal, G. Boulianne, L. Burget, O. Glembek and N. Goel. "The kaldi speech recognition toolkit," In Proc. of IEEE 2011 Workshop on ASRU, 2011.
- [5] D. Povey, D. Kanevsky, B. Kingsbury, B. Ramabhadran, G. Saon and K. Visweswariah. "Boosted MMI for model and feature-space discriminative training," In Proc. International Conference on Acoustics, Speech and Signal Processing (ICASSP), 2008.
- [6] G.E. Dahl, D. Yu, L. Deng and A. Acero. "Context-dependent pre-trained deep neural networks for large-vocabulary speech recognition." IEEE Transactions on Audio, Speech, and Language Processing, vol. 20, no. 1, pp. 30-42, 2012.
- [7] G. Heigold, V. Vanhoucke, A. Senior, P. Nguyen, M. Ranzato, M. Devin, et al. "Multilingual acoustic models using distributed deep neural networks," In Proc. of ICASSP, 2013, pp. 8619–8623.
- [8] G. Hinton, L. Deng, D. Yu, G.E. Dahl, A. Mohamed, N. Jaitly, et al. "Deep neural networks for acoustic modeling in speech recognition: The shared views of four research groups." Signal Processing Magazine, IEEE, vol. 29, no. 6, pp. 82-97, 2012.
- [9] H.M.S. Naing, A.M. Hlaing, W.P. Pa, X. Hu, Y.K. Thu, C. Hori, et al. "A Myanmar large vocabulary continuous speech recognition system," In Proc. of APSIPA Annual Summit and Conference, 2015, pp. 320-327.
- [10] J.G. Fiscus. "A post-processing system to yield reduced word error rates: recognizer output voting error reduction (ROVER)," In IEEE Workshop on ASRU, 1997, pp.347-354.

- [11] J. Long, E. Shelhamer and T. Darrell. "Fully convolutional networks for semantic segmentation," In Proc. CVPR, 2015.
- [12] L. Mangu, E. Brill and A. Stolcke. "Finding consensus among words: lattice-based word error minimization," In Proc. Eurospeech, 1999, pp. 495-498.
- [13] L.R. Rabiner. "A tutorial on hidden Markov models and selected applications in speech recognition." In Proc. IEEE, vol.77, no. 2, Feb. 1989.
- [14] L.R. Rabiner and B.H. Juang. *Fundamentals of Speech Recognition*, Prentice-Hall, Englewood Cliff, New Jersey, 1993.
- [15] M. Gibson and T. Hain. "Hypothesis spaces for minimum Bayes risk training in large vocabulary speech recognition," In Proc. INTERSPEECH, 2006, pp. 2406-2409.
- [16] M. Lin, Q. Chen and S. Yan. "Network in network," arXiv preprint arXiv: 1312.4400, 2013.
- [17] N. Kanda, R. Takeda and Y. Obuchi. "Elastic spectral distortion for low resource speech recognition with deep neural networks," In Proc. of ASRU, 2013, pp. 309-314.
- [18] O. Abdel-Hamid, A. Mohamed, H. Jiang, L. Deng, G. Penn and D. Yu. "Convolutional neural networks for speech recognition." *IEEE/ACM Transactions on Audio, Speech and Language Processing*, vol. 22, no. 10, pp. 1533-1545, 2014.
- [19] P.R. Dixon, C. Hori and H. Kashioka. "Development of the SprinTra WFST speech decoder," *NICT Res. J.* 59 (3/4), pp.15-20, 2012.
- [20] P. Sermanet and Y. LeCun. "Traffic sign recognition with multi-scale convolutional networks," In Proc. of IEEE 2011 International Joint Conference in Neural Networks (IJCNN), 2011, pp. 2809-2813.
- [21] P. Shen, X. Lu, N. Kanda, M. Saiko and C. Hori. "The NICT ASR system for IWSLT 2014," In Proc. IWSLT, 2014, pp. 113-118.
- [22] S.F. Chen and J. Goodman. *An Empirical Study of Smoothing Techniques for Language Modeling*, TR-10-98, Computer Science Group, Harvard University, 2008.
- [23] T.N. Sainath, A. Mohamed, B. Kingsbury and B. Ramabhadran. "Deep convolutional neural networks for LVCSR," In Proc. ICASSP, 2013, pp. 8614-8618.
- [24] T. Sercu, C. Puhersch, B. Kingsbury and Y. LeCun, "Very deep multilingual convolutional neural networks for LVCSR," In Proc. ICASSP, 2016, pp. 4955-4959.
- [25] Ujjwalkarn. (2016). "An explanation of CNN." [On-line], Available: <https://ujjwalkarn.me/2016/08/11/intuitive-explanation-convnets/> [Aug. 22, 2017].
- [26] X. Cui, J. Xue, B. Xing and B. Zhou. "A study of bootstrapping with multiple acoustic features for improved automatic speech recognition," In Proc. INTERSPEECH, 2009, pp. 240-243.