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KAZAKHSTAN

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HANDWRITTEN TEXT RECOGNITION FOR CHAGATAI MANUSCRIPTS: COMPARING CRNN TRAINING FROM SCRATCH AND TRANSFORMER-BASED TRANSFER LEARNING

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Abstract. The digitization of archival Chagatai manuscripts is limited by the scarcity of annotated corpora and the complexity of Arabic-based cursive scripts. This study evaluates two Handwritten Text Recognition (HTR) approaches: a Kraken-based CRNN trained from scratch and a transformer-based TrOCR model using transfer learning. Experiments were conducted on 2531-line images from the Jarring Collection with page-level data splitting to prevent data leakage. Architecture-specific augmentation strategies were applied to address data scarcity. The TrOCR model fine-tuned on augmented data achieved the best performance, reaching a Character Error Rate (CER) of 10.6% and a Word Error Rate (WER) of 35.59%. Data augmentation improved recognition performance for both evaluated architectures, with the augmented configurations achieving lower CER and WER than their respective baselines. The results indicate that transfer learning provided a more effective initialization strategy for the investigated Chagatai corpus under limited data conditions. The study establishes an initial experimental benchmark for Chagatai manuscript recognition.

Keywords: Handwritten Text Recognition (HTR), Chagatai manuscripts, Kraken, TrOCR, transfer learning, data augmentation, low-resource languages

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ШАҒАТАЙ ҚОЛЖАЗБАЛАРЫНЫҢ МӘТІНІН ТАНУ: CRNN-ДІ НӨЛДЕН БАСТАП ОҚЫТУ МЕН ТРАНСФОРМЕР НЕГІЗІНДЕГІ ТРАНСФЕРЛІК ОҚЫТУДЫ САЛЫСТЫРУ

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Аннотация. Архивтік шағатай қолжазбаларын цифрландыру аннотацияланған корпустардың тапшылығымен және араб графикасына негізделген курсивті жазудың күрделілігімен шектеледі. Бұл зерттеуде қолжазба мәтінін тануды (HTR) екі тәсілі бағаланады: нөлден бастап оқытылған Kraken негізіндегі CRNN және трансферлік оқытуды қолданатын трансформатор негізіндегі TrOCR моделі. Эксперименттер деректердің жылыстауын болдырмау үшін бет деңгейінде бөлінген Гуннар Ярринг коллекциясының (Gunnar Jarring Collection) 2531 жол кескінінде жүргізілді. Деректер тапшылығы мәселесін шешу үшін әр архитектураға тән деректерді аугментациялау стратегиялары қолданылды. Аугментацияланған деректермен жетілдірілген TrOCR моделі ең жоғары нәтижеге қол жеткізіп, таңба деңгейіндегі қателер коэффициентін (CER) 10,6% және сөз деңгейіндегі қателер коэффициентін (WER) 35,59% құрады. Деректерді аугментациялау бағаланған екі архитектураның да тану өнімділігін жақсартты, бұл ретте аугментацияланған конфигурациялар тиісті базалық үлгілерге қарағанда төмен CER және WER көрсеткіштеріне жетті. Нәтижелер трансферлік оқытудың зерттелген шағатай корпусы үшін деректер көлемі шектеулі жағдайда тиімдірек инициализация стратегиясын қамтамасыз еткенін көрсетеді. Зерттеу шағатай қол-

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жазбаларын тану үшін бастапқы эксперименталды бенчмарк белгілейді.

Түйінді сөздер: Қолжазба мәтінін тану (HTR), шағатай қолжазбалары, Kraken, TrOCR, трансферлік оқыту, деректерді аугментациялау, аз ресурсты тілдер

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РАСПОЗНАВАНИЕ РУКОПИСНОГО ТЕКСТА ШАГАТАЙСКИХ РУКОПИСЕЙ: СРАВНЕНИЕ ОБУЧЕНИЯ CRNN С НУЛЯ И ТРАНСФЕРНОГО ОБУЧЕНИЯ НА БАЗЕ ТРАНСФОРМЕРОВ

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Аннотация. Цифровизация архивных чагатайских рукописей ограничена нехваткой аннотированных корпусов и сложностью курсивного письма на основе арабской графики. В данном исследовании оцениваются два подхода к распознаванию рукописного текста (HTR): CRNN на базе Kraken, обучаемая с нуля, и модель TrOCR на базе трансформера с использованием трансферного обучения. Эксперименты проводились на изображениях 2531 строки из коллекции Гуннара Ярринга (Gunnar Jarring Collection) с разбиением данных на уровне страниц

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для предотвращения утечки данных. Для решения проблемы нехватки данных были применены стратегии аугментации, специфичные для каждой архитектуры. Модель TrOCR, дообученная на дополненных данных, продемонстрировала наилучшие результаты, достигнув коэффициента ошибок на уровне символов (CER) 10,6% и коэффициента ошибок на уровне слов (WER) 35,59%. Аугментация данных улучшила показатели распознавания для обеих оцениваемых архитектур, при этом конфигурации с аугментацией достигли более низких значений CER и WER по сравнению с базовыми моделями. Результаты показывают, что трансферное обучение обеспечивает более эффективную стратегию инициализации для исследуемого чагатайского корпуса в условиях ограниченного объема данных. Исследование устанавливает начальный экспериментальный бенчмарк для распознавания чагатайских рукописей.

Ключевые слова: распознавание рукописного текста (HTR), чагатайские рукописи, Kraken, TrOCR, трансферное обучение, аугментация данных, низкоресурсные языки

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Introduction.

Historical manuscripts constitute an essential source of linguistic, cultural, and historical knowledge. Their large-scale digitization has therefore become an important objective of digital humanities and computational linguistics. Although Optical Character Recognition (OCR) and Handwritten Text Recognition (HTR) have achieved remarkable progress over the last decade, this progress has been driven primarily by high-resource languages supported by extensive annotated corpora. Consequently, many historical and low-resource languages remain insufficiently explored from the perspective of modern text recognition.

Chagatai, a historical Turkic literary language that served as a major written language across Central Asia for several centuries, represents one such case. Numerous Chagatai manuscripts have been preserved in archival collections, including the Jarring Collection, yet their large-scale digital transcription remains challenging because of handwritten Arabic-based script variability and the scarcity of annotated training data. To the best of our knowledge, publicly documented HTR resources specifically

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developed for Chagatai manuscripts remain scarce and are not yet sufficient for comprehensive benchmarking and comparative evaluation.

Recent studies have demonstrated promising results for low-resource OCR and HTR in related languages, including Kazakh, Uyghur, and Mongolian. Likewise, substantial progress has been achieved in Arabic-script text recognition through transformer-based architectures and transfer learning. Nevertheless, these studies primarily focus on either modern language varieties or languages with substantially different manuscript characteristics. As a result, it remains unclear whether their conclusions can be directly transferred to historical Chagatai manuscripts, where both the amount of annotated data and the paleographic characteristics differ considerably.

This study addresses this research gap by constructing and evaluating two fundamentally different recognition pipelines for Chagatai manuscripts: (1) a Kraken-based model trained entirely from scratch and (2) a TrOCR model fine-tuned from a pre-trained handwritten text recognition checkpoint. Both approaches are evaluated using the same page-level corpus partition and evaluation protocol, with baseline and augmented training considered for each pipeline. This setup provides a direct comparison between from-scratch and transfer-learning approaches under low-resource conditions and allows the effect of data augmentation on recognition error to be assessed.

The contributions of this work are threefold. First, we construct a line-level experimental corpus for Chagatai handwritten text recognition from annotated materials in the Jarring Collection and define a page-level partitioning and evaluation protocol. Second, we compare two learning paradigms: a Kraken-based CRNN trained from scratch and a pretrained Transformer-based TrOCR model fine-tuned using the same page-level data partition. Third, we evaluate both pipelines with and without data augmentation using CER and WER and further analyze their training behavior and representative recognition errors.

The results contribute to a better understanding of the relationship between transfer learning and data augmentation in low-resource handwritten text recognition. Beyond the specific case of Chagatai, the proposed evaluation framework may also serve as a reference for future studies on other historical and low-resource manuscript collections. From a practical perspective, the evaluated models provide a basis for semi-automated transcription of archival Chagatai manuscripts and may reduce the manual effort required for subsequent digitization and analysis.

Literature Review

Handwritten Text Recognition (HTR) has become an important tool for the digitization and analysis of historical manuscripts. The growing use of HTR for improving access to historical sources and supporting large-scale textual analysis has been described (Nockels et al., 2024). Recent reviews trace the development of HTR from template-based methods to deep learning systems and identify document degradation as a continuing source of recognition errors (AlKendi et al., 2024). Progress in HTR has been strongest for languages with large annotated datasets. Historical scripts with limited digital resources remain more difficult to recognize,

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particularly within the Perso-Arabic writing tradition, where handwriting variation and limited training data complicate model development. These constraints were examined in the context of few-shot HTR, demonstrating the need for methods that can operate with limited annotated material (Souibgui et al., 2022).

Research on Turkic and Arabic-script handwriting has produced several datasets that support model development and evaluation. Nurseitov et al. (2021) introduced the HKR database for Kazakh and Russian handwriting recognition. Toiganbayeva et al. (2022) developed the KOHTD dataset for Kazakh handwriting and included samples from thousands of examination papers. For Uyghur, Simayi et al. (2020) presented an unconstrained online word-recognition dataset addressing the connected structure of right-to-left Arabic-based writing. Bouchal et al. (2025) introduced the KALIMA dataset for historical Arabic manuscripts, with attention to stylistic variation and differences in manuscript conditions. Saeed et al. (2024) developed the Muharaf dataset, which contains more than 36,000 historical Arabic text lines. Majeed and Hassani (2024) proposed the Syriac KHAMIS dataset. Earlier resources such as the VML-HD corpus (Kassis et al., 2017) and the RASM2018 scientific manuscript collection (Clausner et al., 2018) have also been used to evaluate handwritten and historical document recognition.

These resources provide useful training and evaluation material, but their linguistic and paleographic characteristics differ from those of historical Chagatai manuscripts. Modern Kazakh and Uyghur datasets do not represent the full range of handwriting variation found in historical Chagatai sources. Historical Arabic and Syriac datasets address some related script characteristics but concern different languages, writing conventions, and manuscript traditions. This distinction is relevant when assessing whether recognition methods developed for related scripts can be transferred to Chagatai.

Model development for Arabic-based handwritten scripts has increasingly moved toward end-to-end and segmentation-free recognition. The transition from character-level processing toward architectures that recognize complete text sequences has been described (Tuama et al., 2025). It has been reported that end-to-end recognition can handle positional character variation and ligature formation in Arabic handwriting (Aabed et al., 2024). Transformer-based architectures have further expanded this line of research. The TrOCR model, which combines a vision Transformer encoder with a pretrained language-model decoder, was recently introduced (Li et al., 2023). Its pretrained representations allow the model to be adapted to new recognition tasks with less task-specific training data than required when training a model entirely from scratch. Other studies have proposed architectures for specific Arabic-script recognition problems. HATFormer (Chan et al., 2024) and the ET-Network (Hamza et al., 2024) address long-range dependencies in historical Arabic and Urdu text, respectively. A hybrid architecture combining Vision Transformers with a BERT-based decoder has been investigated (Ganai et al., 2023). The MMU-OCR-21 benchmark for Urdu text recognition was established in earlier work (Nasir et al., 2021).

Data augmentation represents another line of research for recognition under

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limited training-data conditions. Generative Adversarial Networks for augmenting Kazakh manuscript data have been investigated (Yeleussinov et al., 2023). A stroke-based augmentation that modifies character structure while retaining properties of historical calligraphy was proposed (Ayyoob et al., 2024). Such methods differ from conventional geometric and photometric transformations and provide additional ways to increase training-data variation. Recent work has also examined the use of large multimodal models for historical and low-resource scripts. Cases in which multimodal models generated linguistically plausible but incorrect transcriptions for Kazakh Arabic script have been reported (Gagnier et al., 2026). These findings indicate that high-capacity generative models do not remove the need for domain-specific evaluation and annotated reference data. Few studies directly compare a CRNN system, such as Kraken (Kiessling, 2019), trained from scratch with a pretrained Transformer-based HTR system on the same historical Chagatai corpus. The existing literature provides datasets and recognition methods for several Turkic, Arabic, and other Arabic-script languages, but historical Chagatai remains underrepresented in systematic HTR evaluation. The available resources differ from Chagatai in language, script use, manuscript provenance, or writing characteristics. Few studies directly compare a CRNN system trained from scratch with a pretrained Transformer-based HTR system on the same historical Chagatai corpus. The role of image augmentation under this setting is also insufficiently documented. This study addresses these gaps by evaluating a Kraken CRNN trained from scratch and a pretrained TrOCR model fine-tuned on Chagatai manuscript data. The models are evaluated under a common page-level corpus partition, with and without augmented training data, using CER and WER as the primary recognition metrics.

Materials and methods.

The experiments used a corpus of historical Chagatai manuscripts from the Jarring Collection at Lund University Library. The corpus contains five manuscripts identified as Prov. 2, Prov. 3, Prov. 4, Prov. 8, and Prov. 24. Ground-truth transcriptions were based on the annotated materials of the Annotated Turki Manuscripts from the Jarring Collection Online (ATMO-1 and ATMO-2) projects. The selected manuscript pages were processed in eScriptorium, where text-line regions and their corresponding transcriptions were prepared and manually checked. The resulting annotations were exported together with the coordinates of the line regions. These coordinates were subsequently parsed programmatically and used to crop the corresponding line images from the manuscript pages, producing the final line-level image–text pairs used in the HTR experiments. The resulting corpus contains 2,531 line-level image–text pairs from 230 manuscript pages. The pages represent five Chagatai manuscripts from the Jarring Collection. Line images were exported in PNG format with the corresponding UTF-8 transcription files. The distribution of pages and line images is presented in Table 1.

The corpus was partitioned at the manuscript-page level. This procedure prevented line images from the same page from being distributed across different subsets. All lines extracted from a given page were assigned to the same subset. The

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dataset was divided into training, validation, and test subsets using an 80/10/10 page-level split. The training subset contained 184 pages, the validation subset contained 23 pages, and the test subset contained 23 pages. The split used a fixed random seed of 42. The validation subset was used for training monitoring and checkpoint selection. The test subset remained held out until the final evaluation. The experiments used the exported line images without manual image preprocessing. No binarization, denoising, or contrast adjustment was applied. The ground-truth transcriptions were also retained in their original form. No character-level normalization, kashida removal, or ligature standardization was performed. The original annotation format was preserved during training and evaluation.

Table 1. Corpus composition

Manuscript	Pages	Line images
Prov. 2	86	820
Prov. 3	10	77
Prov. 4	25	227
Prov. 8	56	705
Prov. 24	53	702
Total	230	2531

The page-level partition ensures that text lines from the same manuscript page are not distributed across the training, validation, and test subsets, which helps prevent direct data leakage between the subsets. However, the split is not manuscript-independent, since pages from the same manuscript may still appear in different subsets. Therefore, the test results reflect recognition performance on unseen pages from the manuscripts included in the dataset rather than generalization to entirely unseen manuscripts or scribal traditions.

Two HTR systems were evaluated. The first system used Kraken with a convolutional recurrent neural network (CRNN) architecture. The model was trained from scratch using the Chagatai training data. Its architecture is presented in Table 2. The second system used TrOCR with the pretrained microsoft/trocr-base-handwritten checkpoint from the Hugging Face Transformers library. The two systems used different output representations. Kraken used an alphabet of 73 unique characters. The CTC blank symbol increased the output space to 74 classes. TrOCR used the XLM-RoBERTa tokenizer. Chagatai-specific characters absent from the original vocabulary were added to the tokenizer. The decoder embedding matrix was resized after vocabulary expansion. No frequency threshold was applied when adding the new characters.

Kraken was trained with the ketos training engine and a batch size of 16. Training used early stopping with a patience of 10 epochs based on validation CER. TrOCR was fine-tuned for 60 epochs with a batch size of 32. The baseline configuration used a learning rate of 2×10^{-4}. The augmented-data configuration used a learning rate of 1×10^{-4}. TrOCR training used a cosine learning-rate scheduler with a warm-up ratio of 0.1 and a weight decay of 0.01. The Kraken and TrOCR experiments followed

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separate training procedures. Kraken used ketos-based early stopping, whereas TrOCR used a fixed 60-epoch schedule. The two frameworks also used different batch sizes and optimization settings. The comparison therefore concerns final recognition performance under the specified model configurations rather than identical optimization dynamics. The lower learning rate in the augmented TrOCR experiment was part of the experimental configuration. Therefore, the difference between the baseline and augmented TrOCR results reflects the combined effect of the augmented training data and the corresponding learning-rate setting. This factor is considered when interpreting the augmentation results. All experiments were conducted on an NVIDIA H200 GPU. The software environment consisted of Python 3.11, PyTorch 2.9.0, Transformers 5.14.1, Kraken 6.0.3, and Albumentations 2.0.8. The main training parameters are summarized in Table 3.

Table 2. Kraken CRNN architecture

Layer	Type	Filters / hidden units	Parameters
C_0	ActConv2D	32 filters	1.3K
C_3	ActConv2D	32 filters	40.0K
C_6	ActConv2D	64 filters	55.4K
C_9	ActConv2D	64 filters	110K
L_12	TransposedSummarizingRNN	400 units	1.9M
L_14	TransposedSummarizingRNN	400 units	963K
L_16	TransposedSummarizingRNN	400 units	963K
O_18	LinSoftmax	74 classes	29.7K

Table 3. Training parameters

Parameter	Kraken	TrOCR
Framework	Kraken Ketos	Hugging Face Transformers
Training strategy	From scratch	Fine-tuning
Backbone	CRNN	microsoft/trocr-base-handwritten
Batch size	16	32
Training schedule	Early stopping (patience=10)	60 epochs
Learning rate	Default Ketos configuration	2×10^{-4}
Augmented training LR	-	1×10^{-4}
Scheduler	-	Cosine
Warm-up ratio	-	0.1
Weight decay	-	0.01
GPU	NVIDIA H200	NVIDIA H200

Two image augmentation pipelines were implemented with Albumentations. The Kraken pipeline used small-angle rotation, affine shear, elastic deformation, hue and saturation adjustment, brightness and contrast adjustment, Gaussian noise, and Gaussian blur. The TrOCR pipeline used rotation, affine transformation, brightness and contrast adjustment, ISO noise, and either Gaussian blur or motion blur. Two augmented samples were generated from each original training image. Augmented

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images were used only during training. The validation and test subsets contained original images only. The augmentation parameters are listed in Table 4.

Table 4. Data augmentation settings

Transformation	Kraken	TrOCR
Rotation	±1°	±3°
Affine shear	x,y ±2°	x ±3°, y ±1°
ElasticTransform	α=20, σ=6	-
Hue/Saturation	Yes	-
Brightness/Contrast	±0.2	±0.15
Gaussian noise	Yes	-
ISO noise	-	Yes
Gaussian blur	σ 0.2–0.5	Yes
Motion blur	-	Yes
Synthetic images per sample	2	2

The two pipelines used different transformation sets and intensities. These settings were defined separately for the two model configurations and were not treated as a controlled ablation of individual augmentation operations. The augmentation experiments therefore measure the effect of the complete augmentation configuration used for each model.

Model performance was evaluated using Character Error Rate (CER) and Word Error Rate (WER). Predictions were decoded after removing special tokens. CER and WER were calculated with the Hugging Face Evaluate library. Validation metrics were recorded during training. For model selection, the checkpoint with the lowest validation CER was selected for each experiment. The selected checkpoint was then evaluated on the held-out test set. The test set was not used for training, checkpoint selection, or other training decisions. Training behaviour was examined through the validation metrics recorded across epochs. For Kraken, validation character accuracy was used to describe the training trajectory. For TrOCR, validation CER and WER were examined across epochs. These metrics were analyzed within each model family. They were not used as a common quantitative measure for direct comparison of training trajectories.

The accuracy of the handwritten text recognition model is evaluated using the Character Error Rate (CER), calculated according to formula (1):

$$CER = \frac{(S+D+I)}{N}, \tag{1}$$

where S is the number of character substitutions;

D is the number of character deletions;

I is the number of character insertions;

N is the total number of characters in the reference text (Ground Truth).

Similarly, the word-level recognition accuracy is evaluated using the Word Error Rate (WER), calculated according to formula (2):

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$$WER = \frac{(S_w + D_w + I_w)}{N_w}, \quad (2)$$

where S_w is the number of word substitutions;
D_w is the number of word deletions;
I_w is the number of word insertions;
N_w is the total number of words in the reference text (Ground Truth).

Results.

The recognition performance of the two handwritten text recognition (HTR) pipelines was evaluated under four experimental configurations: Kraken trained from scratch, Kraken with data augmentation, TrOCR fine-tuned from a pretrained checkpoint, and TrOCR fine-tuned using augmented training data. All configurations were evaluated on the same held-out test set defined by the page-level 80/10/10 partition described in Section 3. Character Error Rate (CER) and Word Error Rate (WER) were used as the primary evaluation metrics. The best-performing checkpoint for each experiment was selected according to validation CER and subsequently evaluated on the test set. The final recognition results are presented in Table 5.

Table 5. Recognition performance of the evaluated HTR models

Model	Training strategy	CER (%)	WER (%)
Kraken	Baseline	18.15	55.44
Kraken	Data augmentation	15.54	49.67
TrOCR	Baseline	13.42	40.61
TrOCR	Data augmentation	10.6	35.59

The best overall performance was obtained by TrOCR fine-tuned with augmented training data, achieving a CER of 10.60% and a WER of 35.59%. The Kraken baseline produced the highest error rates, with a CER of 18.15% and a WER of 55.44%. Thus, among the four evaluated configurations, the pretrained transformer-based model combined with data augmentation achieved the lowest recognition error at both the character and word levels.

Lower recognition errors were observed for the augmented configurations in both pipelines. For Kraken, data augmentation reduced CER from 18.15% to 15.54% and WER from 55.44% to 49.67%, corresponding to relative reductions of approximately 14.4% and 10.4%, respectively. For TrOCR, the augmented configuration achieved a CER of 10.60% and a WER of 35.59%, compared with 13.42% and 40.61% for the baseline configuration. These differences correspond to relative reductions of approximately 21.0% in CER and 12.4% in WER. However, the baseline and augmented TrOCR configurations used different learning rates. The observed difference for TrOCR should therefore be interpreted as a comparison between the two training configurations rather than as an isolated effect of data augmentation.

The results also demonstrate a clear difference between training a recognition model from scratch and adapting a pretrained model. The baseline TrOCR configuration

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achieved a CER of 13.42% and a WER of 40.61%, outperforming the augmented Kraken configuration, which achieved 15.54% CER and 49.67% WER. Thus, even without augmentation, the pretrained transformer-based model performed better than the CRNN model trained from scratch with additional synthetic samples.

The difference became more pronounced when augmentation was combined with transfer learning. The augmented TrOCR configuration achieved the best results in the study, with a CER of 10.60% and a WER of 35.59%. Relative to the Kraken baseline, this corresponds to reductions of approximately 41.6% in CER and 35.8% in WER.

These results indicate that, under the experimental conditions considered in this study, transfer learning provided a stronger starting point than training the CRNN architecture exclusively on the available Chagatai corpus. Data augmentation further improved both approaches, with the combination of pretraining and augmentation producing the lowest observed recognition error.

Training dynamics

In addition to final test-set performance, validation metrics were examined to characterize the training behaviour of the evaluated configurations. Because the two frameworks use different optimization procedures and expose different training metrics, the validation trajectories were analyzed separately for Kraken and TrOCR rather than treated as directly comparable measures.

For Kraken, validation character accuracy was monitored during training. The augmented configuration exhibited a different validation trajectory from the baseline and reached higher validation performance during training. The additional geometric and photometric variability introduced by the augmentation pipeline therefore affected the optimization behaviour of the CRNN model in addition to improving its final test-set performance.

For TrOCR, validation CER and WER were monitored throughout fine-tuning. Both baseline and augmented configurations showed an overall reduction in recognition errors during training. The augmented configuration achieved lower final test-set CER and WER while maintaining a broadly similar validation trajectory to the baseline configuration. No pronounced instability was observed in the validation curves associated with augmentation.

Figure 1 presents the validation character-accuracy curves for the Kraken experiments, while Figures 2 and 3 show the validation CER and WER curves for the TrOCR experiments, respectively.

The qualitative examples reveal substantial differences in the types and magnitude of recognition errors produced by the two model families. The Kraken baseline frequently generated long sequences of erroneous characters and diacritics, particularly in visually complex lines. In several examples, the output diverged substantially from the reference transcription, indicating difficulties in reconstructing the character sequence from the handwritten input.

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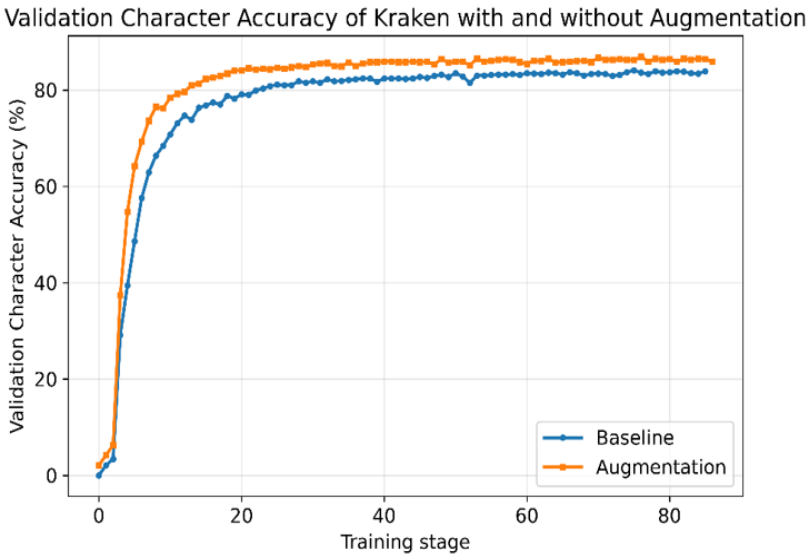


Fig. 1. Validation character accuracy (%) of the Kraken model with and without data augmentation during training

Figure 2 presents the CER curves of the TrOCR models.

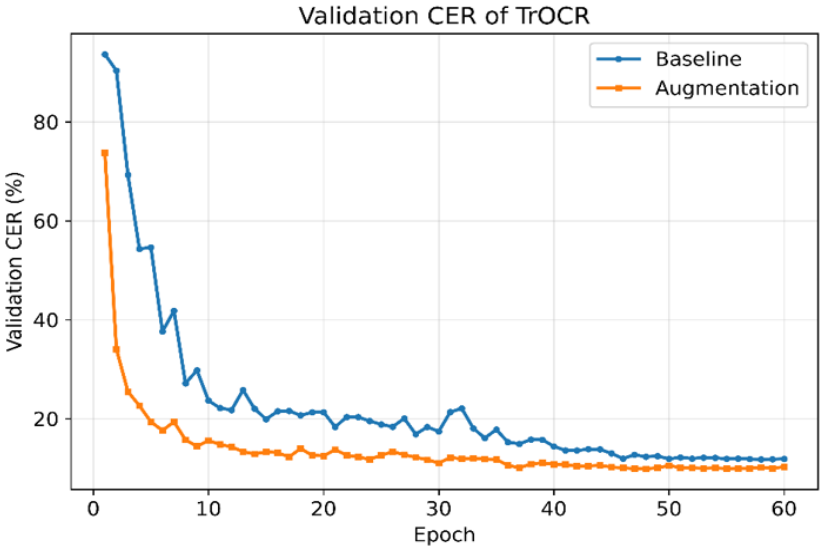


Fig. 2. Character Error Rate (CER) of the TrOCR model with and without data augmentation across training epochs.

Importantly, the validation curves were used only to characterize training behaviour and select model checkpoints according to the experimental protocol. The held-out test set was not used for training, checkpoint selection, or any other optimization decision. Consequently, the quantitative comparison between the four configurations is based on the final test-set CER and WER values reported in Table 5.

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Qualitative Error Analysis

Figure 3 compares the WER obtained during TrOCR training.

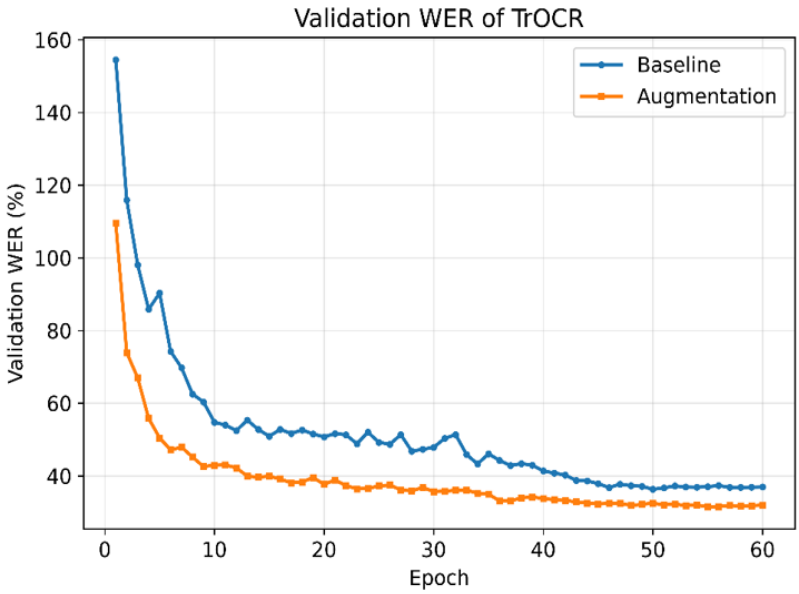


Fig. 3. Word Error Rate (WER) of the TrOCR model with and without data augmentation across training epochs.

Figure 4 summarizes the final recognition performance of all evaluated models.

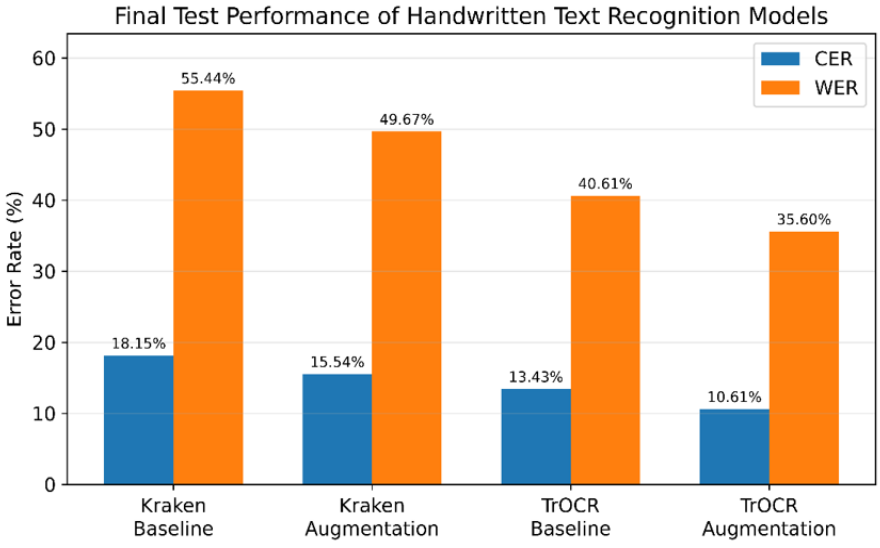


Fig. 4. Final test-set comparison of HTR performance for the Kraken and TrOCR models under baseline and augmentation settings using CER and WER.

The augmented Kraken model generally produced more structured outputs than the baseline model in several examples. Nevertheless, substantial character-level

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errors remained, particularly for lines containing visually complex character forms and diacritic patterns. This observation is consistent with the reduction in aggregate CER and WER reported in Table 5, while also showing that augmentation did not eliminate the recognition difficulties associated with complex manuscript regions. The TrOCR outputs were generally closer to the reference transcriptions and preserved a larger proportion of the original word structure. The augmented TrOCR configuration further improved several representative cases, producing outputs with fewer character substitutions and closer correspondence to individual words in the ground truth. For example, in the selected samples, the augmented model frequently retained the overall lexical structure even when individual characters were incorrectly recognized. However, the effect of augmentation was not uniform across all examples. Some lines showed only limited improvement, while minor differences or additional recognition errors were observed in individual cases. This variability indicates that the effectiveness of augmentation depends partly on the visual characteristics of the manuscript line, including handwriting variation, character forms, and the presence of complex or ambiguous glyphs. Overall, the qualitative analysis is consistent with the quantitative results. Kraken benefited from augmentation but continued to exhibit substantial character-level errors, whereas TrOCR produced more accurate and structurally coherent transcriptions under both training conditions. The augmented TrOCR model provided the strongest performance among the evaluated configurations, although individual recognition errors remained present even in comparatively successful examples.

Discussion.

The results demonstrate that both transfer learning and data augmentation contributed to improved handwritten text recognition of the Chagatai manuscripts, although their effects differed across the evaluated recognition paradigms. The strongest performance was achieved by TrOCR with data augmentation, which obtained the lowest CER and WER among all experimental configurations. Data augmentation also improved the Kraken model, indicating that increasing the visual diversity of the training data was beneficial for both from-scratch training and transfer learning.

To complement the aggregate CER and WER results, a qualitative analysis was conducted using representative manuscript lines with different levels of visual and recognition difficulty. Table 6 presents the ground-truth transcriptions alongside the outputs generated by the four evaluated configurations.

The advantage of TrOCR is particularly relevant in the context of the limited size of the available corpus. The experiments were conducted on 2531 annotated text lines from 230 manuscript pages, which provides only a limited amount of domain-specific material for training a recognition model from scratch. In contrast, the TrOCR model was initialized from a pretrained handwritten text recognition checkpoint, allowing the model to start from representations acquired before adaptation to the Chagatai data.

Table 6. Qualitative comparison of recognition outputs for selected manuscript lines

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ground_truth	kraken_baseline	kraken_augmented	trocr_baseline	trocr_augmented
ینیشاب یشک رکا مساشوت بوروشوت سمیا بوخ مح	حَی َهبِ ْپنِ رَهَ بَتَهبِب رُبَبَتَابَوَبوَبْ َه َهَ ِنْبَ ِب بَبوبَوتَرَب هین ریق هپ پپپنپ ِتره َپْبَبْحَ ِببَبَه ْنرْتَبَوُهَتَتَ تَ ْتَب ِیرَت بَتِرْزِنب رُکرو ریب ارب مِا رکبتَموَبَلَابِّب	ِج ُبیَجْیح ِیَی بَیْجَْیح مْحُسنا ا تَت ول ْلَب ُهِب یشِم انییج ِ بَب ی ح هقچ من هیج یچجن ی ین یچ منیچبحیحی ی ح یاب یسب و مبتیوت یه هی ْرَب ِجْیخ ِوّحوح ِمْ ِی ِاو ُمیّیّسَا ی الا	یشک رکا ینیشاب شات بوروشوت سعا ب دح مهس	یشک رکا ینیشاب بواوشوت بخ مه مسباشرت سیا
میکره رود یشخی ای مدرالغات مدیشوت هویت مدرالری دنلب اک	هْجَا اج ْیَش ْمیکَرَر َهدالورَیمّلَفِی ید را ٌتحْ ِه لکَی وَ ْبَبِب َن ْرَ برروَ اَبَابَبْبِبْبْبَج ُدبِهِب	مدیشوت میکره رو منل ای مدرالیغات اکبویت منراکری وب مکره رورد یشّشم ُهَّم ِیاِیّلاِخُمُبَم	رود یشخی مدیشوت میکره ءمدرالغات یدنلب ای هویت یراکلری اک	رود یشخی مدیشوت میکره ای ءمدرالغات ملریدنلب اک مویتی
ءاشنا یاغبات افش میکره منی و .ملا تداع ینری قاسماس	ییَرق ّو ْضا ءمّنا ابْبَتَتَتَات انْفَفْنبَب بیجک مَصمَوّاهاننا میانَاح ٌتَج ِجْچَتْ ْنب َنْر مِهلَاب ِبح مْبِبیِئبَب	ِلاَب َواق یحی را یَق ْنب ینِاج ّایْب دیجب بی هِح َتْحُح ْاِرمُهل وَمّلا َازْحا لا ا ّی ی ْنی َی ْب ُنْیح	یاغپات افش منی و ملااشنا قاسماس میکره تداع ینری	یاغبات افش منی و ملا أشنا قاسماس میکره تواع ینری
بیقیس ین مبت عفد مسروچیا نومیم میکره یاغلوب رکش ین یتشوک	ل ا ُمکَک َبّحْحب مَبْبرِبلَل ْتَتُکَا َبیَ یَنْرَیْیَپ ٰسرل لیبَب بلَحَاان هّقْهن ابَبْبَب َ بْبَب ٰب بِبْبِباب ٰنمحَ ْتَروَو ِاراِب برَ اِامْر بینبِبَب منَب مب	ْتَب ِیَ محْحَب میل مِه ّمُحلحّج الَمّح َرُولْول ُبّا اا ینیْ الی ْیه یچ نیقیس ینتمبق ِب پات عفرد میسروپچیا میت رب یا بیتاقچ م مابی ج ن ِنْب یوق یل	ین مبت بیقیس عفد مسروچیا میکره یاغلوب یتشوک نیم رکشن	بیقیس ین مبت عفد مسروچیا میکره یاغلوب یتشوک نویم رکفن
معماج مزیکاپ بوی مدغای بیتیپ ةروس مقغای لوا	لتْلا بربرُه ِ ّب َحَق ْب َبَ ِبَاب َاموَرّوت ُرپ اَبِا هْتَبْرِوَب اِرا یْبْرَ َحَتَوالَوَت آتَبَبکبَب ُبْیِ ِنب مَرَ اام اتلتِلَ ِبْبْبارا مْب ِببَحَا ِا ملا ّح ِبلبِباب ْهب َپاِبَبِتْجیبِبِبا ِبْبَ مَجْهعَعا مْبْبِجْر رج وجن مباب منْدَهِحَرُ َو َتَرَرج ّیَلَآتَح بی مسبَبَةاَپ رَرْرِرب ینَا ِهْبی ْبَحْبَ ِبِببَا مبس	یرولا ب ل ّلِل لو ای ْاِیّه ُمْلِه ُنیَ ّالیج جّلب ّالْبْنَ َحَب لب ینْبِو امِوح الب بَوْوُل َقرَلَج لّل ُمرج یت ُیفْ مْجن ْنم منیه ّا ِاالُل اِو اوحُو ْتَ جنی یجن تق یج نی یذْ مح َیلی ّتَّه مهچح یح ّمکاِب مین یج محتلح ِه وِح مِلِلْمُمح ْنْرَ اِج ّرب ُهِب بیبَ ایبْیب	معماج مزیکاپ مدنغای بیتپ مقغ لوا بوی ةروس	معماج مزیکاپ مذغای بیتپ مقغالی لوا بوی ةروس
عمج ین ملچوُک لیکروس بیلیق و رولوب افش لاحرد کنین یشک رگید ره	و ٰبَبَبَحَاِتَبَیّا یتشک ریک ِاب ترج میکیکنی رپ ِالر مجيءپپامپب مک میکربَتَبَرَانن مج َه الب َبَتَیَ َبَبَبَنه ُرَرَبْیِیپ ّهّا َبلَبِ َتَب َوِرُ بَّرو وبا َحاّیی َ ْیلارَبَابَوْرا ٰنبالَلَبَحْ یب مبِلَابَبِرَاّ اِب ینَي یْیَرَبَبِبُهّقَما ِبَتْی	رکد و ِالب ْوحخ ُلم مینک کنین یشک یجینی منره ِچ البْیب ابیو ْیُ ل ْح یابچبیخ ِبْل ی ْلب ِنْبَج ی َ ْنَه ی لاحع رب لیب الاب مریق مدورولوب اقش اِْیَق ّل حْحُب ِنْو ّحو ّ تَمْمُه ُویجوْرُم اِ ْتِل ْلب یمنبْیحْبَ	ین ملچوک بیلیق عمج لاحرد لیکروس و رولوب افش کن یشک رگی کنیت	ین ملیچوک بیلیق عمج لاحرد لیکروس رولوب افش یشک رگی و ره کنید

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داىم الوقاتا ستعمال قىلسا الصا تىشى اغرىماغاى عمرى ايچى	ررا ا مَاوَتا با كَوحَمْتَرَمَرَبىَرْنا رَرا ْتا تَنْ جبْيْنى ا ح ْ تَحنْن تْنا بببْبىبِهِ اْجَهَتَبَ به اپهنى تپه پ ج رَاره بتَبَهبُجبىبَبْرَاتَىَ ل بمبى حاابقهَ پم ر ج ببببُرَهپىَبا بَرْ ب	جولُحَلْلُحُحالُ كَبْحُ كلْمُ ا ُحَعْا ى مَتْتَىَ حْى حا ا ُهُحُ ا ْحْ جمُ ىُخْحْ جىِ ههُمن هرمُىمه ىبى ىقىنى حمام ن منىن ر ت لبىه چ ا قحم حت بچ نچه هنه جقىتى حى حوى من	داىم الدهقات استامال قىلسا الصالتىشى اغرىماغاى عمرى	داىم الوقاتا ستعمال قىلسا الصا تىش اغرىماغاى عمرى ايچى

The lower error rates obtained by the pretrained TrOCR configurations compared with the Kraken configurations therefore suggest that transfer learning can provide an effective initialization strategy when annotated target-domain material is scarce.

Lower recognition error was also observed for the augmented configuration within each model family. For Kraken, where the principal experimental difference was the use of augmented training samples, CER decreased from 18.15% to 15.54% and WER from 55.44% to 49.67%. For TrOCR, CER decreased from 13.42% to 10.60% and WER from 40.61% to 35.59%. However, the TrOCR configurations also differed in learning rate, which prevents the effect of augmentation from being isolated. Therefore, the improvement observed for TrOCR cannot be attributed to data augmentation alone.

The comparison between the two approaches should nevertheless be interpreted carefully. The experimental design does not isolate model architecture from initialization strategy, because Kraken was trained from scratch whereas TrOCR was initialized from a pretrained checkpoint. Consequently, the observed superiority of TrOCR cannot be attributed to the Transformer architecture alone. The results instead demonstrate the effectiveness of the complete Transformer-based transfer-learning configuration evaluated in this study relative to the CRNN configuration trained from scratch. A more controlled experimental design, in which comparable initialization and optimization conditions are applied across architectures, would be required to independently quantify the contributions of architecture and pretraining.

The findings are particularly relevant to HTR for historical and low-resource manuscript collections. Chagatai manuscripts combine several challenging characteristics, including limited annotated resources, variation in handwriting, and the structural complexity of Arabic-based writing. The results suggest that pretrained HTR models can provide a practical starting point for adapting recognition systems to such collections. At the same time, the improvements obtained through augmentation indicate that increasing the visual diversity of a limited training corpus remains valuable even when transfer learning is employed.

The qualitative analysis provides additional insight into the observed quantitative differences. The Kraken configurations frequently produced extensive character-level errors and sequences of incorrectly recognized characters, particularly in visually complex lines. Augmentation reduced these errors in some cases but did not eliminate

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them. TrOCR generally preserved a greater proportion of word structure and produced outputs that were closer to the reference transcriptions. The augmented TrOCR model further improved several difficult examples, although the effect of augmentation was not uniform across all manuscript lines. This variability suggests that augmentation may be particularly useful for some types of handwriting and image variation but may not address all sources of recognition error.

Several limitations should be considered when interpreting these findings. First, the corpus consists of 230 manuscript pages and 2531 annotated text lines from five manuscripts within the Jarring Collection. Although the corpus provides a useful experimental basis for Chagatai HTR, it represents only a limited portion of the broader variation found in historical Chagatai manuscripts. In particular, the range of scribal styles and manuscript conditions is restricted.

Second, the evaluation material originated from the same collection as the training data. Although page-level partitioning prevented lines from the same page from appearing in different subsets, the experiment does not establish how well the trained models generalize to manuscripts produced by different scribes or preserved in other collections. Cross-manuscript and cross-collection evaluation would therefore provide a stronger assessment of model robustness.

Third, the study evaluates two model configurations that differ simultaneously in architecture, initialization, and optimization strategy. Kraken was trained from scratch using the Ketos training framework, whereas TrOCR was fine-tuned from a pretrained checkpoint using a different optimization procedure. The comparison is therefore best understood as a comparison of two practical HTR pipelines rather than as a controlled architectural ablation.

Fourth, the augmentation experiments did not include an ablation study of individual transformations. The augmentation pipelines combined several geometric and photometric operations, and the present experiments therefore cannot determine which transformations contributed most strongly to the observed improvements. In addition, the TrOCR baseline and augmented configurations used different learning rates, which introduces an additional optimization-related factor that should be considered when interpreting the augmentation results.

Future work should address these limitations through broader and more controlled experiments. Evaluation on manuscripts from different collections and scribal traditions would allow the generalization capability of the models to be assessed more rigorously. Ablation experiments could determine the individual contribution of rotation, affine transformations, noise, blur, and other augmentation operations. Additional Transformer-based HTR architectures and parameter-efficient fine-tuning methods could also be evaluated under the same page-level partitioning and test protocol. Furthermore, controlled experiments using comparable initialization and optimization strategies would help separate the effects of architecture, pretraining, and data augmentation.

Overall, the findings indicate that pretrained Transformer-based HTR combined with data augmentation provided the strongest recognition performance among the

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configurations evaluated on the Chagatai manuscript corpus. The results support transfer learning as a promising strategy for low-resource historical HTR, while also demonstrating that synthetic visual variation can provide additional improvements. More broadly, the study provides an empirical basis for further investigation of pretrained HTR models and data-efficient training strategies for historical manuscript collections where large expert-annotated corpora are not yet available.

Conclusion.

This study evaluated two handwritten text recognition paradigms for historical Chagatai manuscripts: a CRNN-based Kraken model trained from scratch and a Transformer-based TrOCR model fine-tuned from a pretrained handwritten text recognition checkpoint. The experiments were conducted on a page-level partition of a corpus comprising 230 manuscript pages and 2531 annotated text lines from five manuscripts in the Jarring Collection. The experimental results demonstrated that data augmentation improved recognition performance for both evaluated HTR pipelines. The best performance was achieved by the augmented TrOCR configuration, which obtained a CER of 10.60% and a WER of 35.59%. In comparison, the Kraken baseline achieved a CER of 18.15% and a WER of 55.44%. The results therefore indicate that the combination of pretrained initialization and synthetic visual variation was the most effective of the evaluated configurations for the investigated low-resource Chagatai corpus. The comparison further showed that the pretrained TrOCR configurations outperformed the Kraken configurations trained from scratch under the experimental conditions of this study. These findings support transfer learning as a promising strategy for HTR when annotated material for a historical language is limited. Data augmentation provides a complementary means of increasing the visual diversity of the training corpus and further reducing recognition errors. The results should nevertheless be interpreted within the scope of the experimental design. The comparison does not independently separate the effects of model architecture, pretrained initialization, and optimization strategy. Therefore, the observed advantage of TrOCR should be understood as the performance advantage of the evaluated Transformer-based transfer-learning pipeline rather than as evidence that the Transformer architecture itself is inherently superior to the CRNN architecture. The study is also limited by the size and provenance of the corpus, which represents five manuscripts from a single archival collection. Generalization across different collections, scribal styles, and manuscript conditions was not evaluated. In addition, the augmentation experiments did not include an ablation study of individual transformations. Future work should therefore investigate cross-manuscript and cross-collection generalization, expand the available Chagatai HTR corpus, systematically evaluate individual augmentation operations, and examine additional Transformer-based and multimodal recognition approaches under controlled experimental conditions. Overall, this study demonstrates the feasibility of applying pretrained HTR models to low-resource historical Chagatai manuscripts and establishes an experimentally evaluated benchmark for comparing from-scratch and transfer-learning approaches. The results provide a foundation for further development of automated recognition systems for Chagatai and other historical Arabic-script Turkic

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manuscript collections, supporting their large-scale digitization and computational analysis.

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