

# Analogical Structure, Minimal Contextual Cues and Contrastive Distractors: Input Design for Sample-Efficient Linguistic Rule Induction

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## Abstract

Large language models achieve strong performance through training on vast datasets. *Can analogical paradigm organization enable lightweight models to match this performance with minimal data?* We develop a computational approach implementing three cognitive-inspired principles: analogical structure, contrastive learning, and minimal contextual cues. We test this approach with structured completion tasks where models identify correct sentence completions from analogical patterns with contrastive alternatives. Training lightweight models (BERT+CNN, 0.5M parameters) on only one hundred structured examples of English causative/inchoative alternations achieves  $F1 = 0.95$ , outperforming zero-shot GPT-o3 ( $F1 = 0.87$ ). Ablation studies confirm that analogical organization and contrastive structure improve performance, consistently surpassing randomly shuffled baselines across architectures. Cross-phenomenon validation using unspecified object alternations replicates these efficiency gains, confirming approach robustness. Our results show that analogical paradigm organization enables competitive linguistic rule learning with orders of magnitude less data than conventional approaches require.

## 1 Introduction

Analogical reasoning, recognizing structural relationships across different contexts, enables efficient learning by abstracting patterns from minimal examples and transferring knowledge to novel situations (Lake et al., 2017). However, this principle has faced persistent scalability challenges across computational approaches: early symbolic systems required extensive knowledge engineering (Forbus et al., 1995), neural word embeddings showed inconsistent performance (Mikolov et al., 2013), and even transformer-based models like BERT show mixed capabilities (Ushio et al., 2021; Thrush et al.,

2020). While recent systems achieve strong performance (Yasunaga et al., 2024; Jiayang et al., 2023; Wijesiriwardene et al., 2023), they still require substantial computational resources or show inconsistent results across complexity levels.

Rather than scaling analogical reasoning systems, we operationalise analogical principles through strategic input organization. Research shows that processing constraints can optimize attention allocation (Christiansen and Chater, 2016), while contrastive learning frameworks show how systematic positive-negative comparisons improve discriminative learning (Chen et al., 2020; He et al., 2020). This suggests that structural organization, not architectural scaling, may unlock analogical efficiency.

In this paper, we develop a computational approach that organizes input data into analogical paradigms through three cognitive-inspired strategies: (i) **Analogical Structure**, systematic paradigmatic relationships supporting pattern recognition; (ii) **Contrastive Learning**, systematically designed distractors enabling discriminative learning; and (iii) **Minimal Contextual Cues**, subtle annotations providing essential semantic information without explicit labeling.

We evaluate this setup using English verb alternations (Levin, 1993) through structured completion tasks based on Blackbird Language Matrices (Merlo, 2023). These tasks require identifying correct sentence completions from systematically organized contexts with contrastive alternatives. Figure 1 illustrates our approach: contexts encode analogical mappings across parallel paradigms (e.g., *Man:Dice :: Exploring:Mat*), requiring models to abstract structural and semantic role relationships rather than memorize surface forms.

Results demonstrate sample efficiency: lightweight models (BERT+CNN,  $\sim 0.5M$  parameters) trained on only 100 structured examples

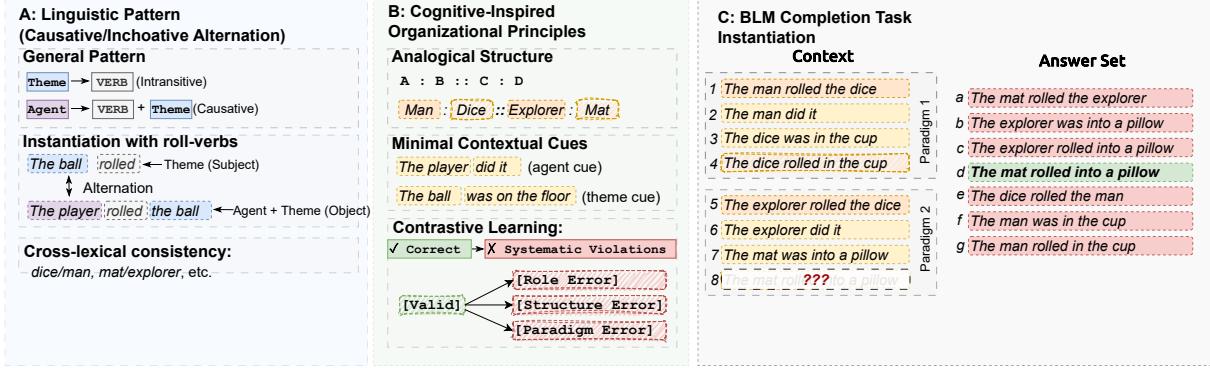


Figure 1: Analogical paradigm organization for sample-efficient linguistic rule learning. (A) Causative/inchoative alternation pattern showing systematic Agent↔Theme mapping in English *roll*-class verbs, with cross-lexical consistency across multiple verb instances. (B) Three cognitive-inspired organizational principles: analogical structure enables cross-paradigm pattern recognition (*Man:Dice :: Explorer:Mat*), contrastive learning provides discriminative boundaries through systematic constraint violations, and minimal contextual cues offer semantic scaffolding without explicit labeling. (C) Implementation through structured completion tasks where models must integrate all three principles to identify correct answer **d** from systematically designed alternatives, each testing specific aspects of analogical reasoning capability (Distractor taxonomy details in Table 1).

achieve  $F1 = 0.95$ , outperforming zero-shot GPT-o3 ( $F1 = 0.87$ ). Cross-phenomenon validation confirms robustness beyond causative constructions.

**Scope:** We operationalise computational algorithms inspired by cognitive principles without claiming to model human cognition directly.

Our contributions are: (i) a computational approach that implements analogical paradigm organization for sample-efficient linguistic rule learning; (ii) empirical evidence that this approach enables competitive performance with minimal training examples; (iii) systematic demonstration that lightweight models can match zero-shot LLM performance on linguistic rule induction tasks.<sup>1</sup>

## 2 Data and Task Design

We operationalize three cognitive-inspired principles through systematic paradigm organization using Blackbird Language Matrices (Merlo, 2023), structured completion tasks that test systematic linguistic rule learning. This section describes our task framework, linguistic domain, and distractor design methodology.

### 2.1 Task Framework

Our completion tasks organize linguistic data into analogical paradigm structures. Each instance contains a structured *Context* comprising two parallel

paradigms encoding analogical relationships (Pattern A ↔ Pattern B), supplemented with minimal contextual cues that provide semantic scaffolding without explicit labeling. It also contains a systematic *Answer Set*: One correct completion that maintains established patterns, and six systematically designed distractors that violate specific structural, semantic, or paradigmatic constraints.

Success requires integrating our three cognitive principles. Models must recognize analogical mappings across paradigms (analogical structure), discriminate between valid and invalid transformations (contrastive learning), and use semantic scaffolding from minimal soft annotations (minimal contextual cues).

### 2.2 Linguistic Test Domain: English Verb Alternations

**Causative/Inchoative Alternations** We use verbs belonging to the *roll*-class (Levin, 1993). These verbs systematically alternate between intransitive (*The ball rolled*) and transitive causative (*The player rolled the ball*) constructions. These alternations require understanding systematic Agent↔Theme mappings where the same entity can serve different grammatical roles depending on causation.

This linguistic phenomenon provides an ideal test case because it requires analogical reasoning across different lexical items sharing the same structural pattern. It also needs to discriminate between valid and invalid argument structure trans-

<sup>1</sup>Code, data, and replication steps will be made publicly available upon publication.

Type	Example	P	S	R	Tests
Correct	<i>The mat rolled into a pillow</i>	✗	✗	✗	All principles (multi-layered analogical reasoning)
RR	<i>The explorer rolled into a pillow</i>	✗	✗	✓	Semantic roles (minimal contextual cues)
SC-RR	<i>The explorer was into a pillow</i>	✗	✓	✓	Syntactic structure (contrastive learning)
SCRS	<i>The mat rolled the explorer</i>	✗	✓	✓	Argument structure (syntax + semantics)
PC-RR	<i>The man rolled in the cup</i>	✓	✗	✓	Cross-paradigm consistency (analogical structure)
PSC-RR	<i>The man was in the cup</i>	✓	✓	✓	Multiple constraints (analogical + contrastive)
PSC-RS	<i>The dice rolled the man</i>	✓	✓	✓	Complex analogical mapping (all principles)

P=Paradigm, S=Structure, R=Role violations

Table 1: Systematic distractor taxonomy testing cognitive principles through hierarchical constraint violations. Each error type violates specific linguistic dimensions (✓) to isolate analogical reasoning components.

formations, and integrate semantic role information with syntactic patterns.

**Cross-Phenomenon Validation** We validate the generalisability of the approach with *bake*-class verbs, a class of verbs exhibiting the unspecified object alternations (*The chef baked a cake* vs. *The chef baked*). In this class, the subject of both the transitive and the intransitive is an *Agent*. While the two classes share syntactic structure, they instantiate semantically distinct processes, testing whether our organizational principles generalize beyond specific semantic classes.

### 2.3 Analogical Paradigm Organization

Figure 1 illustrates our systematic organization approach. Each context follows a  $2 \times 4$  paradigmatic structure.

**Multi-Layered Analogical Structure** Contexts encode analogical relationships at multiple levels: *Man:Dice :: Explorer:Mat* in terms of Agent-Theme relationships, with identical structural transformations applied across different lexical content. This tests whether models can abstract relational patterns beyond surface similarity.

**Minimal Contextual Cues** We provide semantic scaffolding through subtle annotations within each paradigm. For example, action descriptors indicate agentivity (*The player did it*) while state descriptions suggest thematic roles (*The ball was on the floor*). These cues clarify semantic relationships without explicit grammatical labeling.

**Contrastive Learning Through Systematic Distractors** Each answer set implements contrastive learning by providing systematic negative examples alongside each correct completion. Table 1 defines our hierarchical error taxonomy designed to test specific cognitive principles through constraint violations.

Each distractor violates exactly one constraint dimension while preserving others, enabling precise evaluation of rule component acquisition. Role errors (RR) test semantic understanding, structural errors (SC-RR, SCRS) test syntactic knowledge, and paradigm errors (PC-RR, PSC-RR, PSC-RS) test analogical consistency across contexts.

Notice that distractors are contextually inappropriate rather than inherently ungrammatical. For example, *The explorer rolled into a pillow* is grammatical but violates the analogical mapping established in the context.

### 2.4 Data Generation and Availability

Our systematic generation process uses template-based sentence creation with controlled lexical variation and seed alternation pairs, following established verb classifications (Levin, 1993).<sup>2</sup>

## 3 Experiments

We systematically evaluate our analogical paradigm organization approach through controlled experiments testing three core claims: (i) our organizational principles enable sample efficiency compared to unstructured baselines, (ii) individual components contribute systematically to performance, and (iii) lightweight models trained with structured data can match zero-shot reasoning-capable LLM performance on linguistic rule learning. The performance on BLM puzzle completion is used as a proxy for a model’s level of successful linguistic rule learning.

### 3.1 Experimental Design

**Ablation Framework:** We test five systematic conditions that isolate organizational components while controlling information content.

BASE is the complete paradigmatic organization with analogical structure and contextual cues.

<sup>2</sup>Verb class and seed sentences are detailed in Appendix B

SHUFFLED has identical content in random order, (tests organizational vs. content effects). NOANALOGY removes first paradigm (tests analogical structure contribution). NOSOFTCUE removes contextual annotations (tests scaffolding contribution). TRANSPOSED preserves analogical patterns but changes spatial arrangement ( $C_{\text{Trans}} = C_{\text{Base}}^{\top}$ ).<sup>3</sup>

**Data Configurations:** *Type I* uses same verbs across paradigms (3000 examples, 80:10:10 splits, direct analogical mapping). *Type II* uses different verbs across paradigms (15000 examples, same splits, tests abstraction). *Cross-phenomenon* uses unspecified object alternations with *bake*-class verbs (validates generalisability).

**Scale Testing** Training sizes range from 10 to 2700 examples for lightweight models; and 300-example test sets (same as for *Type I* test data, and 300 random examples from *Type II* test set) for LLMs. This balances computational feasibility with statistical reliability for cross-model comparisons.

### 3.2 Models and Training

**Lightweight Models** We use several models of representation. We embed each sentence using BERT<sup>4</sup>(Devlin et al., 2019) as primary model, RoBERTa<sup>5</sup> (Liu et al., 2019) and ELECTRA<sup>6</sup> (Clark et al., 2020) for encoder comparison. We reason that using a weaker base clarifies contributions attributable to data organization rather than encoder capabilities.

As for architecture types, we use previously tested parameter-efficient neural models (CNN and FFNN in Nastase and Merlo (2023) for comparison).(1) CNN captures localized patterns and positional relationships; (2) FFNN processes concatenated embeddings through fully-connected layers, integrating distributed information across the entire context. Both architectures maintain minimal parameter counts ( $\sim 0.5M$  parameters) compared to the encoder ( $\sim 110M$ ), isolating the influence of data organization from architectural capacity. Both models output an answer embedding given the concatenated embeddings of the sentences from the context, evaluated against answer candidates using a max-margin objective with cosine similarity. Training: 120 epochs, learning rate 0.001,

<sup>3</sup>See the formal definitions in Appendix A.1.

<sup>4</sup>bert-base-multilingual-cased

<sup>5</sup>xlm-roberta-base

<sup>6</sup>electra-base-discriminator

Adam Optimizer, batch size 100, early stopping (patience 10). All experiments use random seed 42 with results averaged over 3 independent runs. More model and training details are provided in the Appendix.

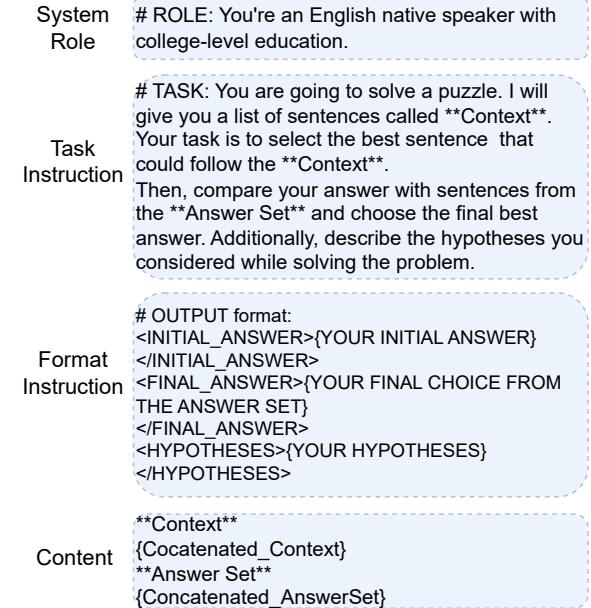


Figure 2: Zero-shot prompt.

**Large Language Models** We evaluate eight advanced models including reasoning-capable systems. *Reasoning models*: deepseek-R1 (DeepSeek-AI, 2025), gpt-o3, gpt-o3-mini,qwq-32B; *Standard models*: deepseek-V3 (DeepSeek-AI, 2024), llama-3.3-70B-Instruct, llama-3.2-3B-Instruct, qwen3-32B. The *temperature* is 0.1 where applicable (standard models), and the *max\_tokens* is 2046.<sup>7</sup>

We test zero, one and five-shot prompting with (w-CoT) and without (wo-CoT) chain-of-thought reasoning (Wei et al., 2021; Kojima et al., 2022). We use a puzzle-solving prompt that parallels our lightweight model setting. A zero-shot example of it is in Figure 2. The LLM first sees the context, generates a provisional answer, then compares it to the answer set before generating the best final sentence (instead of answer key label), and it also generates the hypotheses considered. Any final choice not in the answer set is flagged as a system error (ERR). This prompt mimics our learning objective using pretrained models and presents a more challenging task than standard multiple-

<sup>7</sup>Details on LLM configurations are in Appendix A.1.

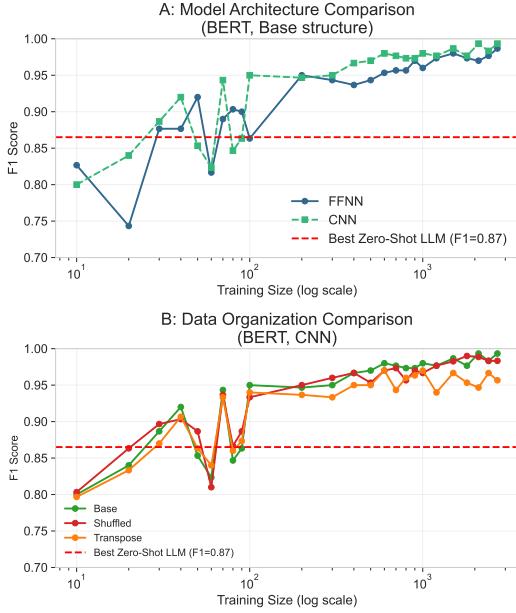


Figure 3: F1 Performance as a function of training size. (A) Comparison of model architectures with BERT embeddings on Base structure organization. (B) Impact of data organization using the best architecture.

choice questions. Randomizing the options in the answer set and asking to generate sentences instead of option labels help debias LLM’s token bias (e.g., A/B/C/D) in multiple-choice-format questions (Zheng et al., 2024). This uniform puzzle-solving format enables direct comparisons across model scales and training paradigms.

**Evaluation** F1 scores balance precision and recall across 7 answer choices. Responses not matching answer set options are flagged as system errors for LLMs. Multi-factor ANOVA tests Structure Model Shots CoT interactions ( $p < 0.05$ ).

### 3.3 Results

We present results from our best-performing architecture (CNN) across all experimental conditions with lightweight models. While both CNN and FFNN demonstrate similar qualitative trends, CNN consistently outperforms FFNN across training regimes, likely due to its capacity to capture local sequential patterns critical for analogical mapping.

#### 3.3.1 Sample Efficiency Validation

Figure 3 confirms our core finding: lightweight models with Base organization achieve  $F1 = 0.95$  with only 100 examples, outperforming our best zero-shot reasoning model GPT-o3 ( $F1 = 0.87$ ). Performance stabilizes at 1000 – 1200 examples

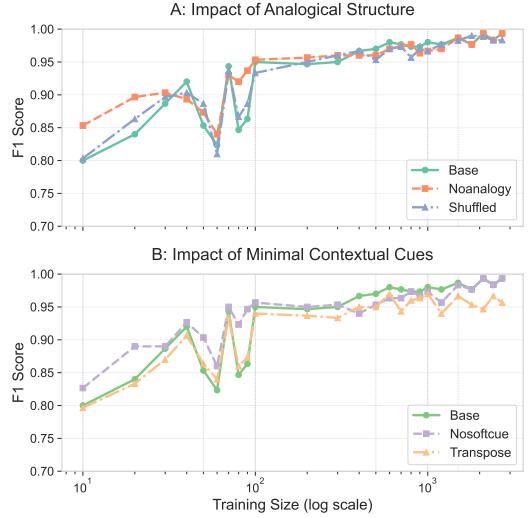


Figure 4: Isolated contributions of organizational components to best model performance. (A) Impact of analogical organisation, comparing BASE against NOANALOGY and SHUFFLED. (B) Impact of implicit soft annotations, comparing BASE with NOSOFTCUE and TRANSPOSED variants.

across architectures. Panel B shows the impact of data organization, where BASE structure outperforms SHUFFLED and TRANSPOSED arrangements. Identical content produces different learning trajectories, confirming that organizational structure, not information quantity, drives efficiency gains.

#### 3.3.2 Component Analysis

Figure 4 validates systematic contributions from individual organizational components. While all structures eventually converge to similar performance levels at larger training sizes, analogical structure (BASE vs. NOANALOGY vs. SHUFFLED) shows slightly more consistent advantages in the 500 – 1,500 example range where data efficiency matters most. Contextual cues (BASE vs. NOSOFTCUE vs. TRANSPOSED) provide additional but smaller benefits.

This subtle differences in learning curves suggest that while both components contribute to learning, modern neural architectures can compensate for deficiencies in either component as training sizes increases.

#### 3.3.3 LLM Comparison

Figure 5 confirms our third contribution: lightweight models trained on 1000 structured examples outperform all tested LLMs in zero-shot conditions, including state-of-the-art reasoning models. Multi-factor ANOVA reveals significant

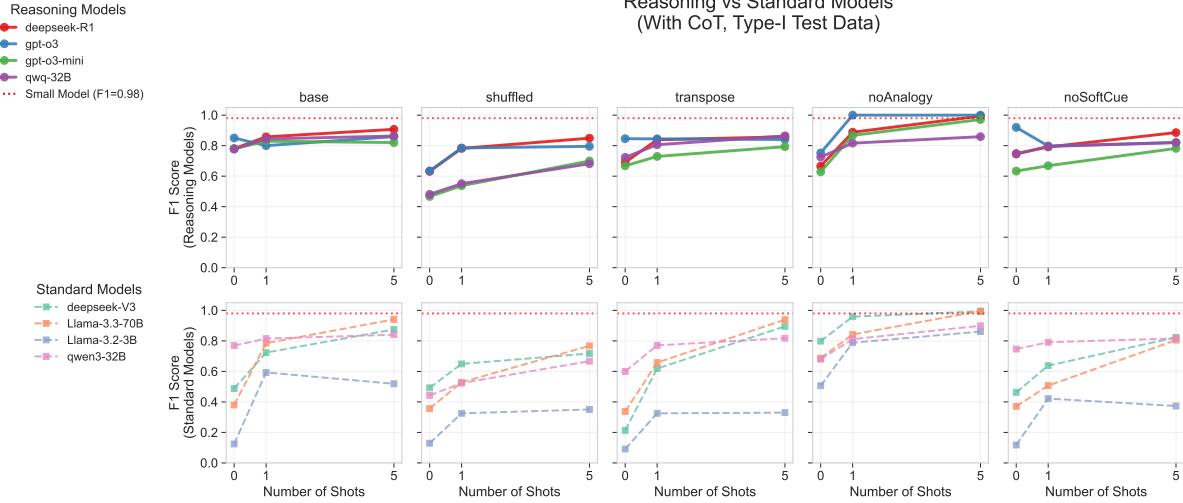


Figure 5: Reasoning models (top row: deepseek-R1, gpt-o3, gpt-o3-mini, qwq-32B) vs. standard models (bottom row: llama-3.3-70B-Instruct, llama-3.2-3B-Instruct, qwen3-32B, deepseek-V3) across data structures. Red dotted line shows small model baseline ( $F1=0.98$ ). Reasoning models consistently outperform standard models, but struggle to match structured lightweight model performance in zero-shot settings.

main effects for Structure, Model, and Shots, with minimal CoT impact<sup>8</sup>. This confirms this task engages pattern recognition and rule application rather than multi-step reasoning.<sup>9</sup>

**Reasoning vs. Standard Models** Reasoning models start with high zero-shot performance ( $F1 = 0.8+$ ) but plateau quickly, while standard models begin lower ( $F1 = 0.1 - 0.5$ ) but show steeper improvement curves, making them more sensitive to organizational structure.

**Organizational Structure Patterns** SHUFFLED consistently performs worst across all models, confirming that random organization disrupts learning. BASE and NOANALOGY emerge as most effective, often performing comparably. Notably, NOANALOGY sometimes outperforms BASE in zero-shot settings for reasoning models, suggesting analogical structure becomes less crucial when models already possess strong reasoning capabilities. However, standard models benefit most from organizational effects that have greater room for improvement.

### 3.4 Error Analysis and Patterns

Figure 6 shows organizational structure affects error patterns across different model types. Lightweight models are robust ( $errors < 3.3\%$ ) across all organizational conditions, demonstrating

<sup>8</sup>Complete results on Multi-factor ANOVA appear in Appendix D.2 (Table 3).

<sup>9</sup>Complete results on LLMs performance are in the Appendix D.3 (Table 4).

consistent learning regardless of structural variations. LLMs show structure-dependent error patterns following our error taxonomy. Disrupted analogical structure (Shuffled condition) causes increased multi-constraint violations, with correct responses dropping from 55% (Base) to 24% (Shuffled) for gpt-o3. This shows that even reasoning-capable models rely heavily on structural organization for linguistic rule learning tasks.

### 3.5 Additional Analysis

**Cross-Phenomenon Generalization** Figure 7 confirms BASE > SHUFFLED hierarchy replicates with *bake*-class verbs. This validates generalisability beyond causative constructions.

**Cross-Type Generalization** Figure 8 demonstrates successful rule abstraction: models achieve robust cross-type performance by 100 – 200 examples, though all conditions eventually converge to high performance with sufficient training data. This confirms learning of structural relationships rather than surface patterns.

**Discussion** Our systematic evaluation validates all three core claims. The finding that lightweight structured models ( $F1 = 0.98$ ) exceed even gpt-o3’s reasoning capabilities ( $F1 = 0.87$ ) demonstrates that systematic input organization can achieve superior linguistic rule learning with reduced computational requirements. The consistent organizational effects across both reasoning and standard LLMs suggest that analogical

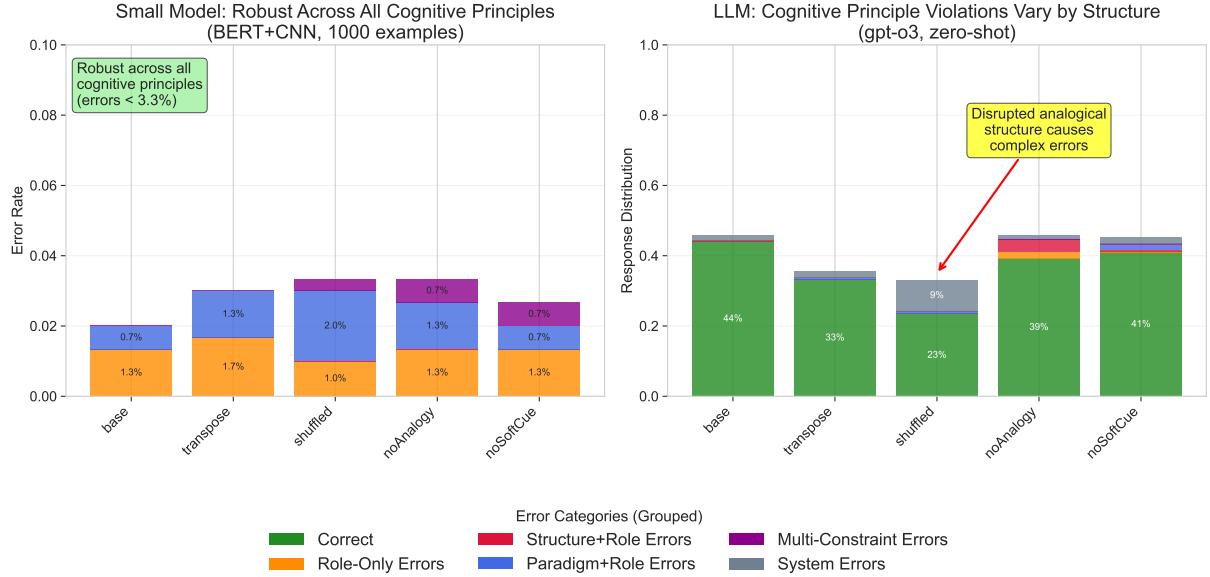


Figure 6: Error analysis across data organizations. Lightweight models (left) show robust performance with minimal errors (< 3.3%) across all structures. LLMs (right, GPT-o3 zero-shot) show structure-dependent error patterns following our cognitive-inspired error taxonomy (Table 1). Shuffled structures particularly disrupt LLMs’ analogical reasoning, causing increased multi-constraint violations.

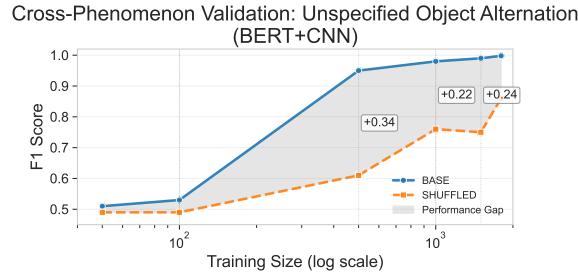


Figure 7: Cross-phenomenon validation using unspecified object alternations (*bake*-class verbs). Results show F1 performance using BERT+CNN architecture on Type-II data, averaged over 3 runs.

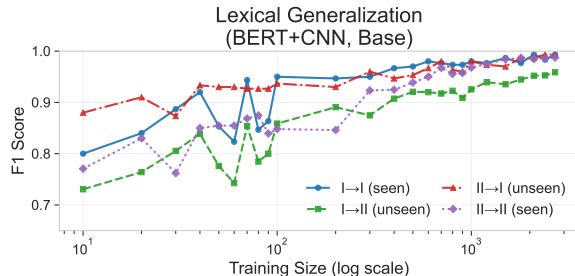


Figure 8: (A) Seen type vs. Unseen Type performance across training sizes.

paradigm organization addresses fundamental challenges in pattern recognition that persist even in the most advanced current systems. The contrasting error patterns between model types suggest that organizational benefits operate through dif-

ferent mechanisms, with accelerated learning for lightweight models and improved error discrimination for LLMs. The cross-phenomenon and cross-type evaluation confirms that our approach captures general principles rather than construction-specific optimizations.

These findings indicate that structured input data organization is complementary to performance gains for linguistic rule learning beyond architectural advances or reasoning capabilities.

## 4 Related Work

**Structured Data for Sample Efficiency** Achieving competitive performance with reduced training needs remains a central challenge in NLP. Recent work emphasizes how reorganizing raw text into structured or hierarchically arranged contexts can significantly enhance model learning (Liu et al., 2024; Sourati et al., 2024). “Structured data” often refers to knowledge graphs, table data, databases (Jiang et al., 2023; Li et al., 2023). Liu et al. (2024) instead reorganize text into hierarchical formats (e.g., Scope-Aspect-Description) to mimic human knowledge consolidation, thereby improving task performance in question-answering. Existing sample efficiency approaches in NLP include data selection (Albalak et al., 2024), data augmentation (Kumar et al., 2020; Dai et al., 2023), curriculum learning (Bengio et al., 2009; Xu et al.,

2020), among others. However, they typically focus on scaling or sequencing existing data rather than fundamental reorganization principles. Our work instead targets linguistic rule learning through structure in a completion tasks inspired by cognitive principles.

**Analogical Learning in Neural Language Models** Analogical reasoning is the ability to perceive and use similarities on relational patterns rather than surface features (Gentner and Smith, 2012). Neural models have shown strong capabilities of analogical reasoning to generalize rules, such as word-level analogies (Mikolov et al., 2013; Brown et al., 2020; Ushio et al., 2021; Webb et al., 2023), concept analogies through analogical structure abduction (Yuan et al., 2023), narrative-based or story-level analogies (Nagarajah et al., 2022; Jiayang et al., 2023; Sourati et al., 2024), or analogical prompting where LLMs generate relevant exemplars or knowledge before solving the problem (Yasunaga et al., 2024). These approaches, like ours, suggest that explicit structural cues improve analogical processing.

**Contrastive Learning in NLP** Contrastive learning has emerged as a powerful principle for neural representation learning. Systematic comparison between positive and negative examples enhances discriminative learning (Chen et al., 2020; He et al., 2020). However, existing contrastive approaches typically require large-scale training data and focus on representation learning rather than rule acquisition. Our systematic distractor design similarly implements a form of contrastive learning by organizing examples that emphasize critical distinctions between alternations. This enables models to learn from the structured contrasts between valid and invalid linguistic transformations.

**Linguistic Rule Learning in Neural Networks** Neural approaches to linguistic rule learning are challenging despite recent advances. Neural language models demonstrate emergent syntactic capabilities (Linzen et al., 2016; Gulordava et al., 2018; Hewitt and Manning, 2019; Mueller et al., 2024) but requires large-scale training. Kann et al. (2019) examine alternations in transformer embeddings with limited success, Thrush et al. (2020) find that systematic selectional preferences require careful training design. LLMs also struggle on metalinguistic tasks (Thrush et al., 2024). Merlo (2023) introduces Blackbird Language Matrices (BLM) as

structured evaluation paradigms for systematic rule assessment, enabling controlled testing of linguistic competence. However, they show limited efficiency in data-lean settings. Our work addresses these efficiency challenges through analogical paradigm organization, building on the BLM framework to achieve competitive argument structure learning with minimal training examples while demonstrating robustness across alternation types.

## 5 Conclusion

We investigated whether computational approaches inspired by cognitive principles can enable sample-efficient linguistic rule learning. Our analogical paradigm organization approach operationalises three organizational strategies, analogical structure, contrastive learning, and minimal contextual cues, through systematic input structuring rather than architectural scaling.

Our results demonstrate substantial sample efficiency gains across multiple evaluation dimensions. Lightweight models (BERT+CNN,  $\sim 0.5M$  parameters) trained on only 100 structured examples achieved  $F1 = 0.95$ , outperforming zero-shot GPT-o3 ( $F1 = 0.87$ ) and stabilizing performance with just 1000 – 1200 training instances. Component analysis confirmed that each organizational principle contributes systematically, with analogical structure showing the largest effect. Cross-phenomenon validation with *bake*-class verbs and cross-type generalization experiments confirmed that benefits extend beyond construction-specific optimizations.

These findings have practical and theoretical implications. Practically, our approach enables competitive linguistic rule learning with much fewer resources than conventional LLM approaches. Theoretically, we demonstrate that systematic input organization can achieve efficiency gains that complement rather than require architectural scaling. This suggests that cognitive-inspired data structuring is a distinct optimization dimension.

Future work should explore cross-linguistic validation, integration with pre-training objectives, and automated structure discovery methods. This research shows that computational approaches inspired by cognitive principles can provide practical advances in sample-efficient linguistic rule learning.

## 6 Limitations

While our approach demonstrates efficiency gains, it is not without limitations.

**Expert Dependency** Our structured paradigms require expert linguistic knowledge to design appropriate analogical mappings and systematic distractors. Although we demonstrate cross-phenomenon generalisability with *bake*-class verbs, scaling this approach to diverse linguistic phenomena would require either linguistic expertise or automated methods for discovering optimal organizational structures.

**Pre-training Attribution** Our lightweight models rely on pre-trained encoders (BERT, RoBERTa, ELECTRA) that already encode linguistic knowledge from unstructured data. This creates attribution challenges in isolating whether performance gains stem purely from our organizational principles or from interactions with pre-existing linguistic representations. While our BASE vs. SHUFFLED comparisons control for this confound, the fundamental attribution question remains.

**Language and Phenomenon Scope** Our evaluation was exclusively on English verb alternations, a specific subset of linguistic phenomena at the syntax-semantics interface. Cross-linguistic validation and extension to other grammatical constructions (e.g., morphological patterns, syntactic transformations) are needed to establish broader applicability of our organizational principles.

**Computational Comparison Framework** Our comparison between trained lightweight models and zero-shot LLMs may not reflect equivalent computational investments. While we demonstrate superior sample efficiency, a fairer comparison might involve fine-tuning LLMs on equivalent structured data or comparing against few-shot learning with similar computational budgets.

**Task Specificity** Our approach targets pattern completion tasks that may favour analogical reasoning. Extension to diverse NLP applications (e.g., generation, reasoning) would provide stronger evidence for the general usability of our organizational principles.

## Ethics

Our research presents minimal ethical concerns. Our synthetically generated data focuses on gram-

matical verb alternations rather than semantic content, minimizing bias propagation risks from LLM training data. Code, data, and experimental procedures will be made publicly available upon publication.

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## A Experimental Setup Details

### A.1 Ablation Design Formalization

We systematically manipulate context structures to isolate organizational components. Given a full context matrix  $C_{\text{full}} \in \mathbb{R}^{m \times n}$  and transformation matrix  $T \in \{0, 1\}^{m \times n}$ , transformed contexts are computed as:

$$C_{\text{trans}} = C_{\text{full}} \odot T$$

### Transformation Matrices

- **NoAnalogy Context**

$$T_{\text{af}} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 0 \end{bmatrix}$$

- **NoSoftCue Context**

$$T_{\text{scf}} = \begin{bmatrix} 1 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \end{bmatrix}$$

- For **Transposed Context**, it simply involves taking the transpose of the full context matrix.

$$C_{\text{trans}} = C_{\text{full}}^T$$

### A.2 Statistical Analysis Framework

**Multi-factor ANOVA Design** Structure (5 levels)  $\times$  Model (8 levels)  $\times$  Shots (3 levels)  $\times$  CoT (2 levels)  $\times$  Data Type (2 levels)

### Generalization Gap Metric

$$\text{GenGap}(t, s) = \frac{1}{|M|} \sum_{m \in M} [F1(m, s, \text{seen}, t) - F1(m, s, \text{unseen}, t)] \quad (1)$$

where  $t$  = training size,  $s$  = structure type,  $M$  = model set, and smaller gaps indicate better generalization.

## B Linguistic Phenomena

### B.1 Causative/Inchoative Alteration (*Roll*-Class Verbs)

The class of *roll* verbs, as categorised by Levin (1993), comprises verbs expressing dynamic actions with inherent motion characteristics. This class shows systematic alternation between:

- **Intransitive:** Theme as subject (e.g., ‘The ball rolled’)
- **Transitive:** Agent causes Theme motion (e.g., ‘The player rolled the ball’)

This syntactic-semantic interface represents a complex mapping challenge for computational models.

**Verb Inventory** The verbs within this class include: *bounce, coil, drift, drop, float, glide, move, revolve, roll, rotate, slide, spin, swing, turn, twirl, twist, whirl*, and *wind*.

### B.2 Cross-Phenomenon Validation (*Bake*-Class Verbs)

Unspecified object alternation with *bake*-class verbs provides syntactically similar but semantically distinct validation:

- **Transitive:** ‘The chef baked a cake’
- **Intransitive:** ‘The chef baked’ (object understood)

This tests whether organizational benefits generalize across alternation types rather than being phenomenon-specific optimizations.

## C Model Implementation

### C.1 Encoder Comparison

We employ BERT (bert-base-multilingual-cased) as our primary encoder to emphasize contributions attributable to data organization rather than encoder capabilities, as evidenced by Figure 9.

### C.2 Architecture Specifications

#### Convolutional Neural Network (CNN)

- Input: Array of embeddings, size  $7 \times 768$
- Convolution layers: Three 2D convolutional layers

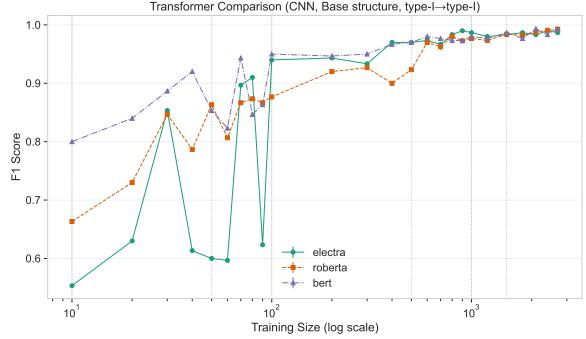


Figure 9: F1 performance as a function of training size, comparing encoder architectures (BERT, RoBERTa, ELECTRA) with CNN architecture on Base structure. Train and test on type I data.

- Kernel size:  $3 \times 3$ , Stride: 1, No dilation
- Output: Fully connected layer compressing to size 768
- Function: Localizes sequential patterns for analogical mapping

### Feed-Forward Neural Network (FFNN)

- Input: Concatenated sentence embeddings, size  $7 \times 768$
- Architecture: Three fully connected layers
- Compression:  $7 \times 768 \rightarrow 3.5 \times 768 \rightarrow 3.5 \times 768 \rightarrow 768$
- Function: Distributed pattern integration across entire context

### C.3 Training Configuration

Models are trained over 120 epochs with learning rate 0.001 using the Adam optimizer and batch size 100. Early stopping with patience 10 prevents overfitting. All models employ a max-margin objective using cosine similarity:

$$\mathcal{L} = \sum_{\mathbf{e}_i \in \mathcal{A}} \max(0, 1 + \cos(\mathbf{e}_i, \mathbf{e}_{\text{pred}}) - \cos(\mathbf{e}_c, \mathbf{e}_{\text{pred}})) \quad (2)$$

where  $\mathbf{e}_c$  is the correct answer embedding,  $\mathbf{e}_i$  are incorrect distractor embeddings, and  $\mathbf{e}_{\text{pred}}$  is the predicted completion. Models are run across three independent trials with seed 42 to ensure statistical reliability.

## C.4 Computational Environment

### Hardware Configuration

- **Workstation:** HP PAIR Workstation Z4 G4 MIT
- **Processor:** Intel Xeon W-2255
- **RAM:** 64 GB
- **GPU:** MSI GeForce RTX 3090 VENTUS 3X OC, 24 GB GDDR6X

### Software Environment

- Ubuntu: 22.04, Python: 3.11.5, CUDA: 11.8.0
- PyTorch: 2.2.2, Transformers: 4.39.1, scikit-learn: 1.5.0
- NumPy: 1.25.0, pandas: 1.4.3

## D Complementary Experimental Results

### D.1 Large Language Model Specifications

We evaluate eight advanced models across four families with varying parameter scales. This systematic comparison allows assessment of how organizational structure affects different model capacities and architectural approaches.

### D.2 Statistical Analysis Results

Complete multi-factor ANOVA results demonstrating significant main effects for Structure, Model, and Shots across all experimental conditions.

### D.3 Comprehensive Performance Results

Complete results across all models, structures, data types, and shot configurations with and without Chain-of-Thought reasoning.

## E Additional Analyses

### E.1 Learning Dynamics Analysis

Figure 10 tracks error reduction as training progresses with the BASE structure. ParadigmChange-RoleReplace errors show the most dramatic decrease, suggesting paradigm-level understanding develops earlier than fine-grained role distinctions. The BASE structure facilitates more efficient error reduction across all types, providing better implicit feedback about linguistic rules consistent with error-driven learning theories.

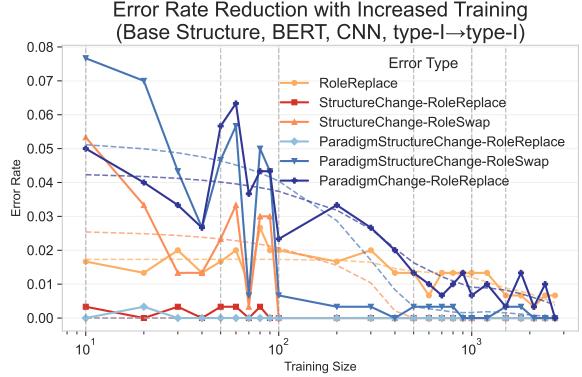


Figure 10: Reduction in error rates as training size increases for the Base structure (train and test on type I data). Dashed lines represent smoothed trends using LOWESS smoothing.

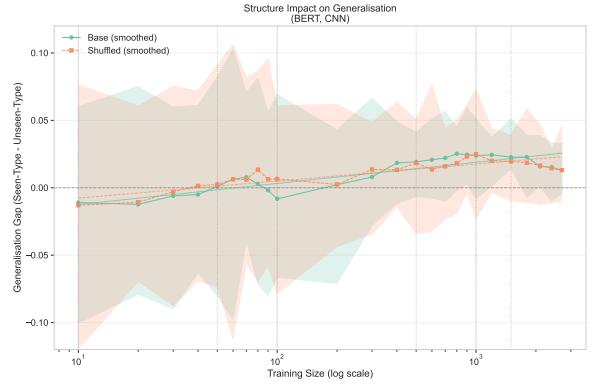


Figure 11: Generalization gap analysis for base and shuffled structures. Smaller gaps indicate better generalization. Base structure facilitates better transfer of linguistic rules to new contexts across all training sizes. Smoothing uses centered rolling window (window size=3) with confidence bands representing standard error propagation.

### E.2 Generalization Analysis

Figure 11 demonstrates that Base structure maintains consistent generalization patterns while Shuffled shows erratic performance in mid-range training sizes. At small training sizes, both structures show negative gaps, suggesting models avoid overfitting to surface lexical patterns. Base structure shows more stable and efficient generalization throughout the learning process.

### E.3 Cross-Phenomenon Validation

Cross-phenomenon validation with *bake*-class verbs confirms that organizational benefits (BASE > SHUFFLED) replicate across different linguistic constructions, validating generalisability beyond causative alternations and demonstrating that our

Model Family	Variant	Parameters	Context	Type	Release
<i>Reasoning Models</i>					
DeepSeek	deepseek-R1-0528	670B	64K	Reasoning	2025-05
OpenAI	gpt-o3	Undisclosed	128K	Reasoning	2025-04
OpenAI	gpt-o3-mini	Undisclosed	128K	Reasoning	2025-01
Alibaba	qwq-32B	32B	32K	Reasoning	2025-03
<i>Standard Models</i>					
DeepSeek	deepseek-V3-0324	671B	64K	Standard	2025-03
Meta	llama-3.3-70B-Instruct	70B	128K	Standard	2024-12
Meta	llama-3.2-3B-Instruct	3B	128K	Standard	2024-09
Alibaba	qwen3-32B	32B	128K	Standard	2025-04

Table 2: Large language models evaluated in experiments. Context window indicates maximum input sequence length in tokens.

approach captures general organizational principles rather than construction-specific optimizations.

Factors	F	p
C(Structure)	9284.541	$p < 0.05$
C(Model)	9581.462	$p < 0.05$
C(Num_Shots)	14125.142	$p < 0.05$
C(CoT)	9.562	$p < 0.05$
C(Data_Type)	191.786	$p < 0.05$
C(Structure):C(Model)	313.487	$p < 0.05$
C(Structure):C(Num_Shots)	170.116	$p < 0.05$
C(Model):C(Num_Shots)	664.883	$p < 0.05$
C(Structure):C(CoT)	2.125	0.0601
C(Model):C(CoT)	3.625	$p < 0.05$
C(Num_Shots):C(CoT)	5.399	$p < 0.05$
C(Structure):C(Data_Type)	115.123	$p < 0.05$
C(Model):C(Data_Type)	37.116	$p < 0.05$
C(Num_Shots):C(Data_Type)	34.928	$p < 0.05$
C(CoT):C(Data_Type)	0.078	0.7795
C(Structure):C(Model):C(Num_Shots)	55.286	$p < 0.05$
C(Structure):C(Model):C(CoT)	1.644	$p < 0.05$
C(Structure):C(Num_Shots):C(CoT)	2.265	$p < 0.05$
C(Model):C(Num_Shots):C(CoT)	1.889	$p < 0.05$
C(Structure):C(Model):C(Data_Type)	13.123	$p < 0.05$
C(Structure):C(Num_Shots):C(Data_Type)	17.556	$p < 0.05$
C(Model):C(Num_Shots):C(Data_Type)	11.177	$p < 0.05$
C(Structure):C(CoT):C(Data_Type)	0.368	0.8709
C(Model):C(CoT):C(Data_Type)	0.214	0.9824
C(Num_Shots):C(CoT):C(Data_Type)	6.551	$p < 0.05$
C(Structure):C(Model):C(Num_Shots):C(CoT)	0.899	0.7079
C(Structure):C(Model):C(Num_Shots):C(Data_Type)	7.100	$p < 0.05$
C(Structure):C(Model):C(CoT):C(Data_Type)	0.919	0.6045
C(Structure):C(Num_Shots):C(CoT):C(Data_Type)	1.748	0.0657
C(Model):C(Num_Shots):C(CoT):C(Data_Type)	1.221	0.2531
C(Structure):C(Model):C(Num_Shots):C(CoT):C(Da...)	0.944	0.6086

Table 3: Multi-ANOVA tests on data (Structure, Data\_Type) and experimental (Model, Num\_Shots, CoT) factors.

Model Config	Base	Noanalogy	Nosoftcue	Shuffled	Transpose
deepseek-R1 (0-shot, w-CoT)	0.743 ± 0.048	0.692 ± 0.037	0.711 ± 0.049	0.614 ± 0.043	0.655 ± 0.050
deepseek-R1 (0-shot, wo-CoT)	0.719 ± 0.063	0.707 ± 0.018	0.720 ± 0.020	0.641 ± 0.030	0.681 ± 0.035
deepseek-R1 (1-shot, w-CoT)	0.857 ± 0.004	0.876 ± 0.048	0.802 ± 0.017	0.788 ± 0.012	0.851 ± 0.028
deepseek-R1 (1-shot, wo-CoT)	0.848 ± 0.009	0.884 ± 0.054	0.802 ± 0.005	0.765 ± 0.021	0.873 ± 0.071
deepseek-R1 (5-shot, w-CoT)	0.884 ± 0.052	0.994 ± 0.004	0.875 ± 0.072	0.871 ± 0.073	0.927 ± 0.076
deepseek-R1 (5-shot, wo-CoT)	0.883 ± 0.058	0.911 ± 0.065	0.866 ± 0.069	0.871 ± 0.073	0.859 ± 0.007
deepseek-V3 (0-shot, w-CoT)	0.537 ± 0.193	0.859 ± 0.089	0.397 ± 0.163	0.445 ± 0.107	0.196 ± 0.130
deepseek-V3 (0-shot, wo-CoT)	0.487 ± 0.409	0.912 ± 0.102	0.630 ± 0.320	0.483 ± 0.410	0.139 ± 0.177
deepseek-V3 (1-shot, w-CoT)	0.729 ± 0.015	0.961 ± 0.008	0.634 ± 0.019	0.620 ± 0.056	0.544 ± 0.082
deepseek-V3 (1-shot, wo-CoT)	0.725 ± 0.011	0.963 ± 0.008	0.632 ± 0.019	0.604 ± 0.033	0.509 ± 0.092
deepseek-V3 (5-shot, w-CoT)	0.895 ± 0.063	0.994 ± 0.002	0.853 ± 0.058	0.703 ± 0.021	0.828 ± 0.100
deepseek-V3 (5-shot, wo-CoT)	0.963 ± 0.007	0.995 ± 0.003	0.899 ± 0.013	0.716 ± 0.036	0.867 ± 0.076
gpt-o3 (0-shot, w-CoT)	0.852 ± 0.008	0.754 ± 0.031	0.844 ± 0.053	0.688 ± 0.041	0.838 ± 0.012
gpt-o3 (0-shot, wo-CoT)	0.884 ± 0.057	0.754 ± 0.022	0.840 ± 0.064	0.700 ± 0.030	0.834 ± 0.015
gpt-o3 (1-shot, w-CoT)	0.891 ± 0.087	0.995 ± 0.012	0.858 ± 0.076	0.783 ± 0.053	0.869 ± 0.066
gpt-o3 (1-shot, wo-CoT)	0.911 ± 0.082	0.990 ± 0.008	0.834 ± 0.031	0.785 ± 0.046	0.894 ± 0.079
gpt-o3 (5-shot, w-CoT)	0.939 ± 0.072	0.998 ± 0.004	0.884 ± 0.094	0.858 ± 0.075	0.922 ± 0.086
gpt-o3 (5-shot, wo-CoT)	0.925 ± 0.078	1.000 ± 0.000	0.842 ± 0.019	0.830 ± 0.033	0.938 ± 0.085
gpt-o3-mini (0-shot, w-CoT)	0.754 ± 0.026	0.629 ± 0.028	0.606 ± 0.044	0.431 ± 0.041	0.641 ± 0.034
gpt-o3-mini (0-shot, wo-CoT)	0.745 ± 0.047	0.644 ± 0.070	0.636 ± 0.052	0.410 ± 0.014	0.573 ± 0.101
gpt-o3-mini (1-shot, w-CoT)	0.809 ± 0.015	0.863 ± 0.055	0.673 ± 0.024	0.542 ± 0.060	0.701 ± 0.063
gpt-o3-mini (1-shot, wo-CoT)	0.812 ± 0.023	0.866 ± 0.059	0.647 ± 0.068	0.551 ± 0.044	0.730 ± 0.068
gpt-o3-mini (5-shot, w-CoT)	0.894 ± 0.076	0.989 ± 0.013	0.774 ± 0.042	0.638 ± 0.044	0.767 ± 0.053
gpt-o3-mini (5-shot, wo-CoT)	0.881 ± 0.086	0.995 ± 0.005	0.764 ± 0.045	0.622 ± 0.053	0.786 ± 0.047
llama-3.2-3B-Instruct (0-shot, w-CoT)	0.093 ± 0.035	0.478 ± 0.033	0.109 ± 0.014	0.118 ± 0.015	0.061 ± 0.033
llama-3.2-3B-Instruct (0-shot, wo-CoT)	0.105 ± 0.042	0.501 ± 0.034	0.112 ± 0.018	0.113 ± 0.015	0.066 ± 0.037
llama-3.2-3B-Instruct (1-shot, w-CoT)	0.524 ± 0.079	0.761 ± 0.031	0.388 ± 0.044	0.279 ± 0.053	0.283 ± 0.049
llama-3.2-3B-Instruct (1-shot, wo-CoT)	0.532 ± 0.055	0.757 ± 0.032	0.374 ± 0.039	0.271 ± 0.057	0.269 ± 0.036
llama-3.2-3B-Instruct (5-shot, w-CoT)	0.456 ± 0.071	0.882 ± 0.045	0.330 ± 0.051	0.317 ± 0.043	0.308 ± 0.031
llama-3.2-3B-Instruct (5-shot, wo-CoT)	0.491 ± 0.063	0.890 ± 0.038	0.313 ± 0.041	0.340 ± 0.051	0.319 ± 0.026
llama-3.3-70B-Instruct (0-shot, w-CoT)	0.304 ± 0.083	0.700 ± 0.015	0.340 ± 0.034	0.337 ± 0.026	0.238 ± 0.110
llama-3.3-70B-Instruct (0-shot, wo-CoT)	0.298 ± 0.087	0.687 ± 0.017	0.309 ± 0.021	0.318 ± 0.018	0.223 ± 0.106
llama-3.3-70B-Instruct (1-shot, w-CoT)	0.774 ± 0.021	0.845 ± 0.046	0.515 ± 0.036	0.491 ± 0.042	0.592 ± 0.073
llama-3.3-70B-Instruct (1-shot, wo-CoT)	0.783 ± 0.047	0.783 ± 0.080	0.499 ± 0.015	0.447 ± 0.046	0.594 ± 0.066
llama-3.3-70B-Instruct (5-shot, w-CoT)	0.964 ± 0.055	0.996 ± 0.001	0.875 ± 0.084	0.737 ± 0.035	0.952 ± 0.045
llama-3.3-70B-Instruct (5-shot, wo-CoT)	0.942 ± 0.071	0.976 ± 0.051	0.870 ± 0.091	0.734 ± 0.021	0.931 ± 0.056
qwen3-32B (0-shot, w-CoT)	0.786 ± 0.122	0.596 ± 0.222	0.736 ± 0.029	0.441 ± 0.009	0.538 ± 0.074
qwen3-32B (0-shot, wo-CoT)	0.659 ± 0.088	0.662 ± 0.059	0.752 ± 0.069	0.429 ± 0.016	0.535 ± 0.065
qwen3-32B (1-shot, w-CoT)	0.808 ± 0.011	0.797 ± 0.018	0.792 ± 0.018	0.532 ± 0.014	0.729 ± 0.046
qwen3-32B (1-shot, wo-CoT)	0.811 ± 0.021	0.788 ± 0.009	0.800 ± 0.012	0.525 ± 0.028	0.740 ± 0.046
qwen3-32B (5-shot, w-CoT)	0.839 ± 0.003	0.896 ± 0.070	0.830 ± 0.017	0.636 ± 0.049	0.815 ± 0.007
qwen3-32B (5-shot, wo-CoT)	0.833 ± 0.009	0.917 ± 0.067	0.842 ± 0.063	0.619 ± 0.021	0.808 ± 0.010
qwq-32B (0-shot, w-CoT)	0.776 ± 0.035	0.724 ± 0.023	0.747 ± 0.026	0.504 ± 0.018	0.672 ± 0.076
qwq-32B (0-shot, wo-CoT)	0.752 ± 0.060	0.732 ± 0.011	0.731 ± 0.036	0.462 ± 0.042	0.652 ± 0.076
qwq-32B (1-shot, w-CoT)	0.843 ± 0.010	0.821 ± 0.015	0.793 ± 0.007	0.598 ± 0.042	0.762 ± 0.056
qwq-32B (1-shot, wo-CoT)	0.843 ± 0.009	0.822 ± 0.015	0.792 ± 0.011	0.600 ± 0.047	0.755 ± 0.048
qwq-32B (5-shot, w-CoT)	0.863 ± 0.006	0.863 ± 0.004	0.831 ± 0.017	0.691 ± 0.021	0.846 ± 0.021
qwq-32B (5-shot, wo-CoT)	0.864 ± 0.002	0.863 ± 0.003	0.829 ± 0.009	0.680 ± 0.017	0.836 ± 0.027

Table 4: Performance (F1 scores in % ± standard deviation) of all LLMs validated across all configurations.