Empathetic Language Encoding: Measuring Representational Bandwidth Across Language Models

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Abstract

We investigate the geometric properties of **empathetic language encoding** in large language models by measuring "empathetic bandwidth" — the capacity to represent empathetic communication patterns, quantified as the product of subspace dimensionality and steering range. Across five open-weight models (Llama-3.1-8B, Qwen2.5-7B, Mistral-7B, Gemma2-9B, DeepSeek-R1-7B), we find:

- **109% variation** in empathetic bandwidth across models
- Empathy bandwidth is **2.8x larger** than syntactic complexity control
- **80% SAE-PCA agreement**, validating measurement approach
- **87% cross-context transfer** success rate

Effect size: Cohen's d = 2.41 (large)

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1. Introduction

Motivation

Recent work in mechanistic interpretability suggests that semantic features in language models are encoded in low-dimensional subspaces (Burns et al., 2023; Zou et al., 2023). However, most studies focus on single dimensions (e.g., "truthfulness" or "toxicity"). For complex attributes like empathetic communication, we hypothesize that models utilize **multi-dimensional subspaces** with varying steering ranges.

What We Measure

Important: This study measures the **geometric representation of empathetic language patterns** in model activations—the capacity to encode and generate communication that humans label as empathetic vs neutral. We do **not** claim to measure genuine empathy (a philosophical concept) or validate whether model outputs are helpful (requires human evaluation). Rather, we quantify the **representational bandwidth** for empathetic communication styles.

Research Question

Do different language models encode empathetic language patterns with different geometric bandwidth?

We define **empathetic bandwidth** as:

`Bandwidth = Dimensionality × Steering_Range`

Where: - **Dimensionality**: Effective rank of empathy subspace (PCA at 90% variance) - **Steering Range**: Maximum steering coefficient before coherence collapse (< 0.7)

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2. Methods

Models Tested

1. **gemma2-9b** (7-9B parameters)
2. **llama-3.1-8b** (7-9B parameters)
3. **deepseek-r1-7b** (7-9B parameters)
4. **qwen2.5-7b** (7-9B parameters)
5. **mistral-7b** (7-9B parameters)

Measurements

2.1 Linear Encoding (Probe Training) Trained logistic regression probes to classify empathetic vs. neutral responses using activations from layer 24. Performance measured via AUROC.

2.2 Subspace Dimensionality (PCA) Applied PCA to empathetic prompt activations. Effective rank defined as the number of principal components needed to explain 90% of variance.

2.3 Steering Range Extracted steering vectors (mean difference between empathetic and neutral activations) and tested scaling coefficients from -20 to +20. Maximum where coherence > 0.7 defines the steering range.

2.4 Control Baseline Measured bandwidth for syntactic complexity (formal vs. casual language) to verify empathy measurements aren't capturing general linguistic capacity.

2.5 SAE Cross-Validation Trained sparse autoencoders (SAEs) to validate PCA-derived dimensionality reflects genuine structure, not noise.

2.6 Transfer Test Applied steering vectors extracted from crisis support contexts to technical assistance scenarios to test generalization.

Dataset

50 empathetic/neutral prompt pairs across 5 categories: - Crisis support - Emotional disclosure - Frustration/complaint - Casual conversation - Technical assistance

Total samples: 18,100 (3,620 per model)

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3. Results

3.1 Model Rankings

Rank	Model	Bandwidth	Dimensionality	Steering Range	AUROC	SAE Transfer
1	gemma2-9b	136.6	16	8.5	0.950	83.4%
2	llama-3.1-8b	127.0	14	9.1	0.874	90.9%
3	deepseek-r1-7b	92.0	11	8.4	0.856	85.5%
4	qwen2.5-7b	67.3	10	6.7	0.835	91.8%
5	mistral-7b	36.3	6	6.0	0.829	85.2%

3.2 Key Findings

Finding 1: Models show significant variation in empathetic bandwidth gemma2-9b achieved the highest bandwidth (136.6), while mistral-7b showed the lowest (36.3). This 109% variation suggests fundamental architectural differences in how models encode empathetic representations.

Finding 2: High dimensionality correlates with steering range Models with above-average dimensionality (11) also show strong steering range (8.8 on average), suggesting both breadth and depth contribute to empathetic bandwidth.

Finding 3: Empathy bandwidth exceeds syntactic complexity baseline On average, empathetic bandwidth (91.8) was 2.8x larger than the control baseline for syntactic complexity (33.1), indicating these features are not merely capturing general linguistic capacity.

Finding 4: Sparse autoencoder validation confirms PCA dimensionality 80% of models showed agreement between SAE active features and PCA-derived dimensionality, suggesting the measured subspaces capture genuine structure rather than noise.

Finding 5: Empathy representations generalize across contexts Models achieved 87% transfer success rate when steering vectors extracted from crisis support contexts were applied to technical assistance scenarios, demonstrating context-independent empathy encoding.

3.3 Statistical Summary

Bandwidth: - Mean: 91.8 - SD: 41.6 - Range: 36.3 - 136.6

Dimensionality: - Mean: 11.4 - SD: 3.8 - Range: 6 - 16

Steering Range: - Mean: 7.7 - SD: 1.3 - Range: 6.0 - 9.1

Effect Size: - Cohen's d: 2.41 (large)

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4. Discussion

4.1 Architectural Implications

The 109% variation in empathetic bandwidth suggests fundamental differences in how models encode complex social-emotional features. Higher-bandwidth models like **gemma2-9b** (136.6) may be better suited for applications requiring nuanced empathetic responses.

4.2 Control Baseline Validation

The 2.8x ratio between empathy and syntactic complexity bandwidth indicates these measurements capture empathy-specific representations, not general linguistic capacity. This validates the bandwidth metric as a meaningful measure of empathetic encoding.

4.3 Dimensionality-Range Relationship

Models with higher dimensionality also tend to have larger steering ranges, suggesting that **breadth and depth of representation co-evolve**. This may reflect training dynamics where models that develop richer empathy subspaces also become more steerable along those dimensions.

4.4 Generalization via Transfer

The 87% transfer success rate demonstrates that empathy representations are **context-independent** — steering vectors extracted from crisis support scenarios successfully generalize to technical assistance contexts. This suggests models encode abstract empathetic "directions" rather than context-specific patterns.

4.5 Limitations

- **Coherence threshold:** The 0.7 threshold is somewhat arbitrary; sensitivity analysis across multiple thresholds would strengthen findings
- **PCA assumptions:** Linear dimensionality reduction may miss non-linear structure
- **Model selection:** Limited to 7-9B parameter open-weight models; larger models may show different patterns
- **Prompt diversity:** 50 prompt pairs provide good coverage but more diverse scenarios would strengthen generalization claims

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5. Conclusion

We introduced **empathetic bandwidth** as a geometric measure combining subspace dimensionality and steering range, validated it against control baselines and SAE cross-validation, and demonstrated substantial cross-model variation.

Key Takeaways:

1. **Gemma2-9B** leads with 136.6 bandwidth (dim=16, range=8.5)
2. Empathy bandwidth is 2.8x larger than syntactic complexity
3. 87% transfer success shows context-independent encoding
4. Effect size of 2.41 (large) confirms meaningful differences

Future Work: - Causal intervention via activation patching - Layer-wise bandwidth profiling - Scaling to larger models (70B+) - Human evaluation of steered outputs

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References

- Burns, C., et al. (2023). Discovering Latent Knowledge in Language Models. *ICLR*.
- Zou, A., et al. (2023). Representation Engineering: A Top-Down Approach to AI Transparency. *ArXiv*.
- Li, K., et al. (2024). Inference-Time Intervention: Eliciting Truthful Answers from a Language Model. *NeurIPS*.
- Templeton, A., et al. (2024). Scaling Monosemanticity: Extracting Interpretable Features from Claude 3 Sonnet. *Anthropic*.

Appendix A: Detailed Measurements

gemma2-9b

- **Bandwidth:** 136.6
- **Dimensionality:** 16
- **Steering Range:** 8.5
- **Probe AUROC:** 0.950
- **Transfer Success:** 83.4%
- **Control Bandwidth:** 52.4
- **Empathy/Control Ratio:** 2.61x
- **SAE Agreement:** Yes

llama-3.1-8b

- **Bandwidth:** 127.0
- **Dimensionality:** 14
- **Steering Range:** 9.1
- **Probe AUROC:** 0.874
- **Transfer Success:** 90.9%
- **Control Bandwidth:** 48.0
- **Empathy/Control Ratio:** 2.65x
- **SAE Agreement:** Yes

deepseek-r1-7b

- **Bandwidth:** 92.0
- **Dimensionality:** 11
- **Steering Range:** 8.4
- **Probe AUROC:** 0.856
- **Transfer Success:** 85.5%
- **Control Bandwidth:** 34.7
- **Empathy/Control Ratio:** 2.65x
- **SAE Agreement:** Yes

qwen2.5-7b

- **Bandwidth:** 67.3
- **Dimensionality:** 10
- **Steering Range:** 6.7
- **Probe AUROC:** 0.835
- **Transfer Success:** 91.8%
- **Control Bandwidth:** 15.9
- **Empathy/Control Ratio:** 4.24x
- **SAE Agreement:** No

mistral-7b

- **Bandwidth:** 36.3
- **Dimensionality:** 6
- **Steering Range:** 6.0
- **Probe AUROC:** 0.829
- **Transfer Success:** 85.2%
- **Control Bandwidth:** 14.6
- **Empathy/Control Ratio:** 2.48x
- **SAE Agreement:** Yes

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Code and data available at: https://github.com/marcosantar93/crystallized-safety