# Developmental Geometry in Facial Embeddings

*A Boundary-Layer Transition*

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CVPR JUNE 3-7, 2026 DENVER COLORADO

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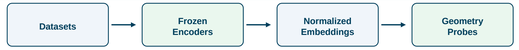
## Why this matters

- Developmental phase is a natural distribution shift for child-centered vision systems.
- If embeddings lie near decision boundaries, retrieval, clustering, identity-linking, or moderation can become age-stratified and brittle.
- This work probes the geometry of frozen CLIP-family encoders rather than benchmarking age prediction.

## Experimental design




| | |
|---|---|
| **Datasets** | UTKFace (>20K), FG-NET |
| **Age bins** | 0-5, 6-12, 13-17, 18-40, 40+ |
| **Encoders** | CLIP-L/14, ViT-H/14, ViT-B/16, DataComp-L |
| **Probes** | kNN purity, centroid shift, margin, flips, LID |

## Developmental bins

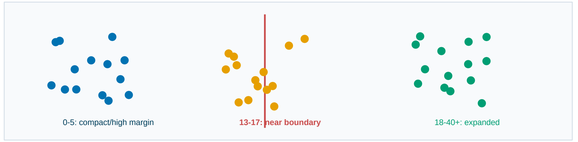
**0-5** | **6-12** | **13-17** | **18-40** | **40+**

Age bins are used as probes of representation geometry, not as a new supervised benchmark.

## Core result in one glance

| Margin | Flip | Purity | LID |
|---|---|---|---|
| 12.9 -> 3.94 | 0.31 -> 0.51 | 0.926 -> 0.315 | ~10.5 -> ~11.9 |
| 0-5 to 13-17 | omega = 0.02 | k = 10 | expands |

**Takeaway:** adolescence behaves like a boundary-layer regime - not a compact cluster - with reduced decision margin and elevated perturbation fragility.




Source: camera-ready paper - values from Tables 1-6 and Figures 1-4. Mean values shown where space requires.

## Embedding manifold structure

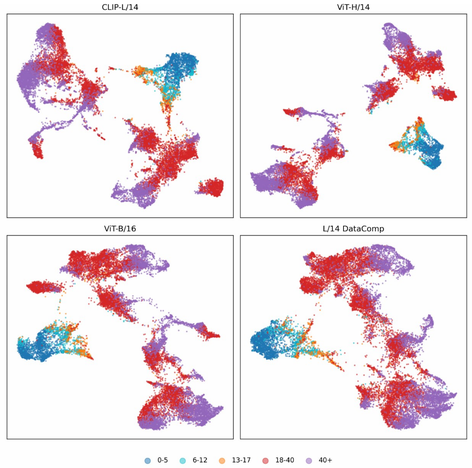



Figure 1: UMAP across four encoders. Adolescence lies between childhood and adulthood rather than forming a compact isolated cluster.

## Centroid shift and continuity

**Centroid distances between consecutive age bins (UTKFace)**

| Model | 0-5->6-12 | 6-12->13-17 | 13-17->18-40 | 18-40->40+ |
|---|---|---|---|---|
| CLIP L/14 | 0.040 | 0.017 | 0.040 | 0.029 |
| ViT-H/14 | 0.123 | 0.051 | 0.106 | 0.081 |
| ViT-B/16 | 0.085 | 0.039 | 0.085 | 0.078 |
| DataComp-L | 0.068 | 0.031 | 0.055 | 0.063 |

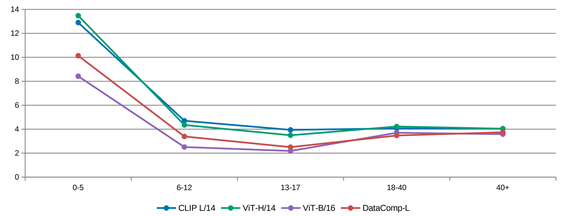
**Mean adjacent-step distance by bin (UTKFace)**

| Model | 0-5 | 6-12 | 13-17 | 18-40 | 40+ |
|---|---|---|---|---|---|
| CLIP L/14 | 0.51 | 0.61 | 0.67 | 0.67 | 0.70 |
| ViT-H/14 | 0.66 | 0.80 | 0.86 | 0.86 | 0.90 |
| ViT-B/16 | 0.57 | 0.70 | 0.74 | 0.71 | 0.81 |
| DataComp-L | 0.58 | 0.70 | 0.77 | 0.79 | 0.84 |

Smallest centroid shift occurs from 6-12 to 13-17, supporting the boundary-layer interpretation.

Source: camera-ready paper - values from Tables 1-6 and Figures 1-4. Mean values shown where space requires.

## Boundary proximity: low margins

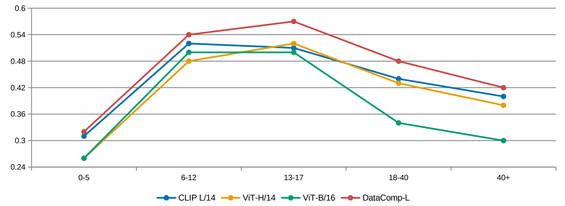



**UTKFace margin means (std omitted)**

| Model | 0-5 | 6-12 | 13-17 | 18-40 | 40+ |
|---|---|---|---|---|---|
| CLIP L/14 | 12.9 | 4.70 | **3.94** | 4.06 | 4.04 |
| ViT-H/14 | 13.47 | 4.35 | 3.49 | 4.22 | 4.04 |
| ViT-B/16 | 8.42 | 2.51 | 2.18 | 3.70 | 3.58 |
| DataComp-L | 10.13 | 3.39 | 2.50 | 3.47 | 3.74 |

Across four encoders, the adolescent bin (13-17) has the lowest or near-lowest decision margin.

## Perturbation fragility peaks



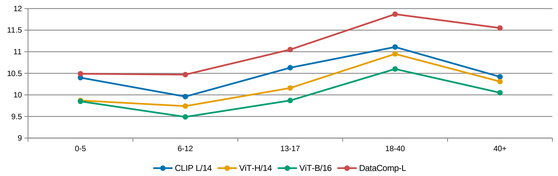

**Boundary flip probability under Gaussian perturbation (omega=0.02)**

| Model | 0-5 | 6-12 | 13-17 | 18-40 | 40+ |
|---|---|---|---|---|---|
| CLIP L/14 | 0.31 | 0.52 | 0.51 | 0.44 | 0.40 |
| ViT-H/14 | 0.26 | 0.48 | 0.52 | 0.43 | 0.38 |
| ViT-B/16 | 0.26 | 0.50 | 0.50 | 0.34 | 0.30 |
| DataComp-L | 0.32 | 0.54 | 0.57 | 0.48 | 0.42 |

Low-margin strata show higher perturbation-induced instability; adolescent flip rates reach 0.50-0.57.

Source: camera-ready paper - values from Tables 1-6 and Figures 1-4. Mean values shown where space requires.

## Intrinsic manifold complexity




**Local intrinsic dimensionality means (UTKFace, k=20)**

| Model | 0-5 | 6-12 | 13-17 | 18-40 | 40+ |
|---|---|---|---|---|---|
| CLIP L/14 | 10.40 | 9.96 | 10.63 | 11.11 | 10.42 |
| ViT-H/14 | 9.87 | 9.74 | 10.16 | 10.95 | 10.31 |
| ViT-B/16 | 9.85 | 9.49 | 9.87 | 10.60 | 10.05 |
| DataComp-L | 10.49 | 10.47 | 11.05 | 11.87 | 11.55 |

## Triangulated signature

| Probe | Pattern | Interpretation |
|---|---|---|
| Centroid | small 6-12 -> 13-17 | transition layer |
| Margin | lowest at 13-17 | boundary-adjacent |
| Flip | 0.50-0.57 | fragile regime |
| LID | increases with age | manifold expansion |

The transition signature replicates across architectures and on two independent datasets.

## Implications and conclusion

- Developmental phase is encoded as geometry, not only as category.
- Adolescence emerges as a boundary-layer between childhood and adulthood.
- Systems relying on embedding stability should test age-stratified brittleness even without explicit age supervision.
- Finding is geometric, not a claim of fairness violation.

**Developmental phases are geometrically stratified regions with differential stability.**

Source: camera-ready paper - values from Tables 1-6 and Figures 1-4. Mean values shown where space requires.

Poster size: 42 in x 21 in (landscape, 2:1). No bleed. CVPR 2026 Denver.