Supplementary

1 How Well Is 3D Information Encoded in the Latent Space of the DAE?

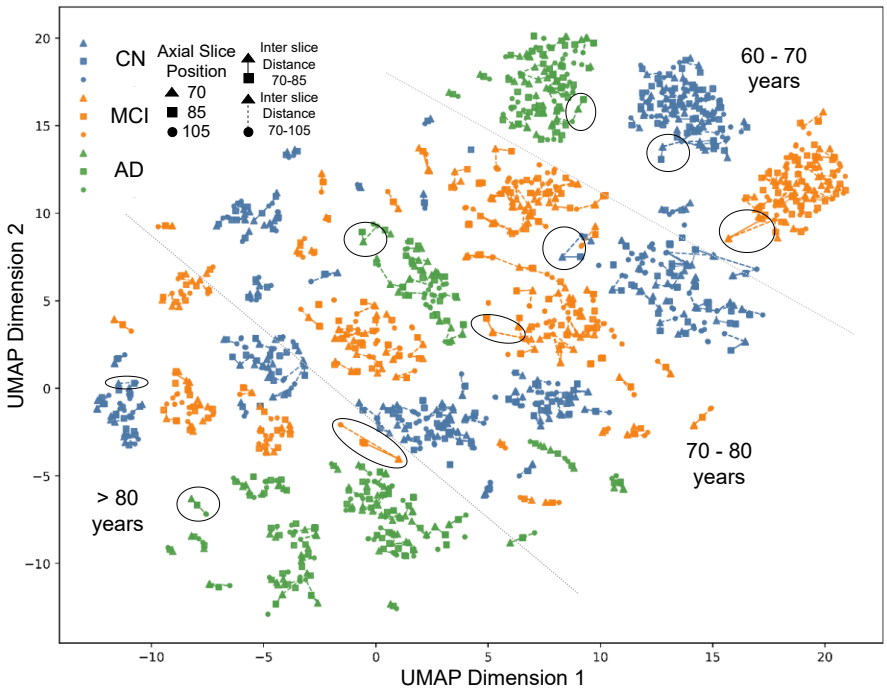

Figure 1: UMAP plot of the latent representations (z) of three axial sections from all the volumes of ADNI *Test Set*. The three slices- 70^{th}, 85^{th}, and 105^{th} along the axial plane are denoted by triangle, square, and circle, respectively. The distances from the 70^{th} to 85^{th} and 70^{th} to 105^{th} are denoted by straight and dashed lines, respectively, for all the volumes. This plot represents that the spatial location of the 3D volumes are meaningfully embedded within the latent representational space.

Figure 1 illustrates the organization of axial slices from 3D volumes at different locations (70^{th}, 85^{th}, and 105^{th}) in the latent representational space of the DAE. Across the embedding space, axial slices originating from the same 3D volume are spatially co-located, indicating consistent encoding of volumetric information.

For each volume, the latent-space distances between the 70^{th} and 85^{th} slices, and between the 70^{th} and 105^{th} slices, are visualized using solid and dashed lines, respectively. Distances corresponding to axially closer slices (solid lines) are relatively smaller than those between axially distant slices (dashed lines). This relationship is observed across disease categories (CN, MCI, and AD, shown in blue, orange, and green) as well as across different age groups.

The spatial co-location of slices from the same volume, together with higher-level grouping by disease category and age, indicates that the latent representational space effectively encodes both subject-specific 3D structural information and progression-related characteristics. Overall, these results suggest that the DAE latent space preserves volumetric coherence while capturing meaningful disease- and age-related variations.

2 Quantitative Evaluation of Progression–Identity Separation in the Latent Space

To quantitatively evaluate whether AD-DAE separates progression-related factors from subject-specific identity in the latent space, we perform a ***latent swap*** experiment on the *Latent Swap Dataset*. In this experiment, the first m latent dimensions ($m = 50$), corresponding to progression-related components, are exchanged between paired subjects prior to image generation, while the remaining $(d - m)$ dimensions are preserved to retain subject identity.

For a paired CN subject x_b^B and AD subject x_b^A, progression-conditioned latent representations are computed as $z_f^{'B} = \mathcal{E}(x_b^B) + [\mathcal{A}(v_d^B, v_a^B); \mathbf{0}]$ and $z_f^{'A} = \mathcal{E}(x_b^A) + [\mathcal{A}(v_d^A, v_a^A); \mathbf{0}]$. Latent swapping is performed by constructing mixed representations $[z_f^{'B}[0:m]; z_f^{'A}[m:d]]$ and $[z_f^{'A}[0:m]; z_f^{'B}[m:d]]$, which are decoded to generate follow-up images $\hat{x}_f^A$ and $\hat{x}_f^B$, respectively.

Progression transfer is quantitatively assessed using normalized ventricular volumes. For AD→CN transformations with an age gap ≥ 2 years, $\hat{X}_f^A$ exhibits a reduced normalized ventricular volume of $V^r_{\hat{X}_f^A}/V_{\hat{X}_f^A} = 0.0105$, compared to 0.0115 for the original AD image $V^r_{X_b^A}/V_{X_b^A}$, indicating ventricular contraction consistent with CN progression. Conversely, for CN→AD transformations with an age gap < 2 years, $\hat{X}_f^B$ shows an increased normalized ventricular volume of 0.0119, relative to 0.0105 in X_b^B, reflecting ventricular enlargement characteristic of AD progression.

Preservation of subject identity is evaluated using image similarity metrics. The PSNR between $(\hat{x}_f^A, x_b^A)$ is 26.01 dB, and between $(\hat{x}_f^B, x_b^B)$ is 25.86 dB, indicating that identity-related anatomical structures are largely preserved despite

the transfer of progression-related factors.

Together, these quantitative results demonstrate that AD-DAE enables controlled transfer of progression-specific anatomical changes while maintaining subject-specific identity, validating effective separation of progression and identity factors in the latent space.