

# Pattern Recognition

## Hyper-HierUDA:Hyperbolic Hierarchical Learning for Unsupervised Domain Adaptation in Semantic Segmentation

--Manuscript Draft--

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Abstract:	<p>Unsupervised Domain Adaptation (UDA) is a key technique for addressing the performance degradation of semantic segmentation models when applied across domains, such as transferring from synthetic to real-world data. Although substantial progress has been made with existing adversarial training and self-training methods, these approaches typically adhere to a “flat” classification paradigm, neglecting the inherent semantic hierarchy among categories. In this work, we propose Hyper-HierUDA, a novel UDA domain generalization strategy that integrates hyperbolic geometry with UDA tasks, significantly enhancing domain generalization by explicitly learning high-level semantic knowledge within hierarchical structures.</p> <p>Specifically, we conduct UDA in hyperbolic space, leveraging its hierarchical properties to move beyond the conventional flat classification paradigm. This enables a progressive classification approach that incorporates richer high-level semantic knowledge for cross-domain generalization. Furthermore, we introduce an explicit learning strategy for high-level concepts within the hierarchy. Building on the progressive classification paradigm, Hyper-HierUDA requires the model to predict not only specific categories but also their corresponding abstract concepts, utilizing these abstract concepts to strengthen the cross-domain generalization of specific category knowledge.</p> <p>Experimental results on the GTA5→Cityscapes and Synthia→Cityscapes benchmarks demonstrate that Hyper-HierUDA achieves state-of-the-art performance and is effective across multiple backbone networks, including DAFormer and DeepLabv3+. Notably, our approach yields significant improvements in small-scale and semantically similar categories, such as “Sidewalk” and “Traffic sign”. Extensive ablation studies and feature analyses further validate that explicit learning within hyperbolic hierarchies produces more discriminative and domain-invariant features, thereby efficiently facilitating cross-domain knowledge transfer.</p>

## Cover letter

Dear Editors,

We would like to submit our manuscript, Hyper-HierUDA: Hyperbolic Hierarchical Learning for Unsupervised Domain Adaptation in Semantic Segmentation, to Pattern Recognition. The paper proposes a hyperbolic, hierarchical path-wise decoder for unsupervised domain adaptation (UDA) in semantic segmentation, trained in an EMA self-training regime. By embedding pixel features into the Poincaré ball (constant negative curvature) and explicitly supervising intermediate (abstract) nodes along root-to-leaf paths, our method encourages hierarchy-consistent decisions and reduces confusions among rare and visually similar classes.

Why it fits PR.

Pattern Recognition welcomes principled advances that improve robustness and generalization in real-world recognition scenarios. Our work integrates a geometry-aware representation with a structure-aware decoder and a standard, strong UDA training protocol, providing both methodological novelty and practical gains on widely used benchmarks.

Relation to our prior PR article (2022).

Cycle-reconstructive subspace learning with class discriminability for unsupervised domain adaptation (PR, 2022) addressed UDA via cycle reconstruction and subspace learning. The present work targets semantic segmentation with a hyperbolic hierarchical decoder and EMA self-training, using different objectives, architectures, datasets, analyses, and results.

Comparison to State-of-the-Art.

Our study includes comprehensive comparisons against state-of-the-art methods. The following five articles represent recent SOTA in semantic segmentation UDA, which we have compared against in our experiments:

Wang, Q., et al. (2022). DAFormer: Improving Network Architectures and Training Strategies for Domain-Adaptive Semantic Segmentation. CVPR.

D. Zhao, et al. (2023). Learning pseudo-relations for cross-domain semantic segmentation. ICCV.

Ma, et al. (2023). I2f: A unified image-to-feature approach for domain adaptive semantic segmentation. TPAMI.

J. Li, et al. (2024). Feature re-representation and reliable pseudo label retraining for cross-domain semantic segmentation. TPAMI.

C. Zhu, et al. (2025). Hard-aware instance adaptive self-training for unsupervised cross-domain semantic segmentation. TPAMI.

Our method demonstrates superior performance, particularly in handling fine-grained and rare classes, by leveraging hierarchical constraints that these flat-classification-based SOTA methods overlook.

Public Datasets Used.

We utilized the following standard public benchmarks for UDA in semantic segmentation:

GTA5: A synthetic dataset with 24,966 labeled images, used as the source domain.

Cityscapes: A real-world urban driving dataset with 2,975 training images, used as the target domain.

Our primary experiments and analysis are conducted on the GTA5 → Cityscapes adaptation task. Additionally, we report results on Synthia→Cityscapes to further validate the generalizability of our approach.

#### Validation Measures Used.

Following the standard evaluation protocol in semantic segmentation UDA, we used the following metrics:

Mean Intersection over Union (mIoU): This is the primary metric for evaluating semantic segmentation accuracy, measuring the average overlap between predicted and ground-truth segments across all classes. We report per-class IoU and the mean IoU.

Mean Accuracy (mAcc): This metric is used as a complementary measure to assess the model's pure classification accuracy at the pixel level, independent of the inherent class imbalance in the dataset. It is particularly valuable in our work for evaluating the model's discriminative capability and its sensitivity to class imbalance, which is a central challenge in UDA tasks.

Our choice of mIoU as the main metric ensures direct comparability with the vast majority of literature in this field.

#### Originality, ethics, and concurrent submissions.

This manuscript is original, not published, and not under consideration elsewhere. All authors comply with PR's ethics, authorship, and conflict-of-interest policies. We will publicly release the source code, configuration files, and hierarchy definitions upon acceptance to ensure full reproducibility.

#### Data, code, and reproducibility.

We will release code, configuration files, hierarchy definitions, and scripts (with seeds) to facilitate full reproducibility (anonymized link upon request or public release upon acceptance).

#### Conflicts of interest.

The authors declare no conflicts of interest. We will avoid suggesting reviewers with any potential COIs.

Thank you for your consideration. We believe the paper's combination of geometry-aware modeling, hierarchy-aware decoding, and carefully controlled UDA evaluation will be of strong interest to the Pattern Recognition readership.

Sincerely,

Hua Yan, on behalf of all authors

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# Hyper-HierUDA:Hyperbolic Hierarchical Learning for Unsupervised Domain Adaptation in Semantic Segmentation

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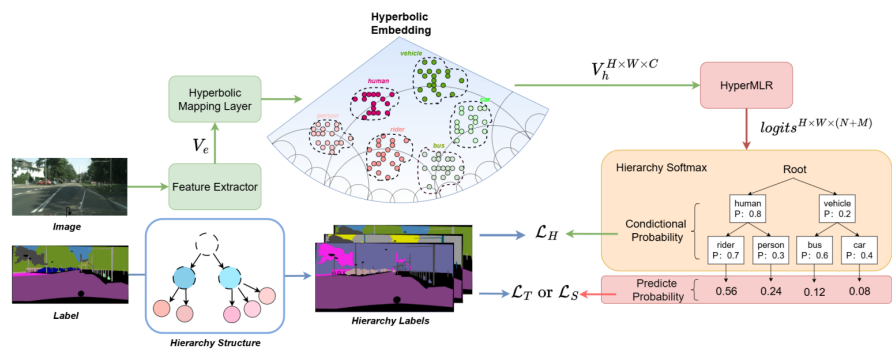
## ORCID IDs:

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# Graphical Abstract

## Hyper-HierUDA:Hyperbolic Hierarchical Learning for Unsupervised Domain Adaptation in Semantic Segmentation

Xiaokang Zhou, Hua Yan



## Highlights

### **Hyper-HierUDA: Hyperbolic Hierarchical Learning for Unsupervised Domain Adaptation in Semantic Segmentation**

Xiaokang Zhou, Hua Yan

- Pioneering use of hyperbolic geometry for hierarchical learning in UDA semantic segmentation.
- A novel progressive hyperbolic classification framework enhances domain generalization.
- An explicit learning strategy leverages domain-invariant, high-level abstract semantics.
- Achieves state-of-the-art results, with significant gains on small objects.

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integers (HO)
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)
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line 72
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LaTeX Font Info:      Trying to load font information for OMS+txsy on input
line

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```

72.
(c:/texlive/2024/texmf-dist/tex/latex/txfonts/omstxsy.fd
File: omstxsy.fd 2000/12/15 v3.1
)
LaTeX Font Info:    ... okay on input line 72.
LaTeX Font Info:    Checking defaults for OT1/cmr/m/n on input line 72.
LaTeX Font Info:    ... okay on input line 72.
LaTeX Font Info:    Checking defaults for T1/cmr/m/n on input line 72.
LaTeX Font Info:    ... okay on input line 72.
LaTeX Font Info:    Checking defaults for TS1/cmr/m/n on input line 72.
LaTeX Font Info:    ... okay on input line 72.
LaTeX Font Info:    Checking defaults for OMX/txex/m/n on input line 72.
LaTeX Font Info:    Trying to load font information for OMX+txex on input
line
72.
(c:/texlive/2024/texmf-dist/tex/latex/txfonts/omctxex.fd
File: omctxex.fd 2000/12/15 v3.1
)
LaTeX Font Info:    ... okay on input line 72.
LaTeX Font Info:    Checking defaults for U/txexa/m/n on input line 72.
LaTeX Font Info:    Trying to load font information for U+txexa on input
line 7
2.
(c:/texlive/2024/texmf-dist/tex/latex/txfonts/utxexa.fd
File: utxexa.fd 2000/12/15 v3.1
)
LaTeX Font Info:    ... okay on input line 72.
LaTeX Font Info:    Checking defaults for PD1/pdf/m/n on input line 72.
LaTeX Font Info:    ... okay on input line 72.
LaTeX Font Info:    Checking defaults for PU/pdf/m/n on input line 72.
LaTeX Font Info:    ... okay on input line 72.
(c:/texlive/2024/texmf-dist/tex/context/base/mkii/supp-pdf.mkii
[Loading MPS to PDF converter (version 2006.09.02).]
\scratchcounter=\count316
\scratchdimen=\dimen185
\scratchbox=\box66
\nofMPsegments=\count317
\nofMParguments=\count318
\everyMPshowfont=\toks32
\MPscratchCnt=\count319
\MPscratchDim=\dimen186
\MPnumerator=\count320
\makeMPintoPDFobject=\count321
\everyMPtoPDFconversion=\toks33
) (c:/texlive/2024/texmf-dist/tex/latex/epstopdf-pkg/epstopdf-base.sty
Package: epstopdf-base 2020-01-24 v2.11 Base part for package epstopdf
Package epstopdf-base Info: Redefining graphics rule for '.eps' on input
line 4
85.
(c:/texlive/2024/texmf-dist/tex/latex/latexconfig/epstopdf-sys.cfg
File: epstopdf-sys.cfg 2010/07/13 v1.3 Configuration of (r)epstopdf for
TeX Liv
e
) (c:/texlive/2024/texmf-dist/tex/latex/graphics/color.sty

```



Package: color 2024/01/14 v1.3d Standard LaTeX Color (DPC)  
(c:/texlive/2024/texmf-dist/tex/latex/graphics-cfg/color.cfg  
File: color.cfg 2016/01/02 v1.6 sample color configuration  
)

Package color Info: Driver file: pdftex.def on input line 149.  
(c:/texlive/2024/texmf-dist/tex/latex/graphics/mathcolor.ltx))  
Package hyperref Info: Link coloring ON on input line 72.  
(./Manuscript .out) (./Manuscript .out)  
\@outlinefile=\write4  
\openout4 = `"Manuscript .out".

Package caption Info: Begin \AtBeginDocument code.  
Package caption Info: rotating package is loaded.  
Package caption Info: End \AtBeginDocument code.  
LaTeX Font Info: Trying to load font information for TS1+lmr on input  
line 1  
47.  
(c:/texlive/2024/texmf-dist/tex/latex/lm/ts1lmr.fd  
File: ts1lmr.fd 2015/05/01 v1.6.1 Font defs for Latin Modern  
)

Overfull \hbox (2.22221pt too wide) has occurred while \output is active  
[]  
[]

[1

{c:/texlive/2024/texmf-  
var/fonts/map/pdftex/updmap/pdftex.map}{c:/texlive/2024/  
texmf-dist/fonts/enc/dvips/lm/lm-ec.enc}{c:/texlive/2024/texmf-  
dist/fonts/enc/d  
vips/lm/lm-ts1.enc}}  
LaTeX Font Info: Trying to load font information for OT1+lmr on input  
line 1  
70.  
(c:/texlive/2024/texmf-dist/tex/latex/lm/ot1lmr.fd  
File: ot1lmr.fd 2015/05/01 v1.6.1 Font defs for Latin Modern  
)  
LaTeX Font Info: Trying to load font information for OML+lmm on input  
line 1  
70.  
(c:/texlive/2024/texmf-dist/tex/latex/lm/oml1mm.fd  
File: oml1mm.fd 2015/05/01 v1.6.1 Font defs for Latin Modern  
)  
LaTeX Font Info: Trying to load font information for OMS+lmsy on input  
line  
170.  
(c:/texlive/2024/texmf-dist/tex/latex/lm/omslmsy.fd  
File: omslmsy.fd 2015/05/01 v1.6.1 Font defs for Latin Modern  
)  
LaTeX Font Info: Trying to load font information for OMX+lmex on input  
line

```

170.
(c:/texlive/2024/texmf-dist/tex/latex/lm/omxlmex.fd
File: omxlmex.fd 2015/05/01 v1.6.1 Font defs for Latin Modern
)
LaTeX Font Info: External font `lmex10' loaded for size
(Font) <10> on input line 170.
LaTeX Font Info: External font `lmex10' loaded for size
(Font) <7> on input line 170.
LaTeX Font Info: External font `lmex10' loaded for size
(Font) <5> on input line 170.
LaTeX Font Info: Trying to load font information for OTl+txr on input
line 1
70.
(c:/texlive/2024/texmf-dist/tex/latex/txfonts/otltxr.fd
File: otltxr.fd 2000/12/15 v3.1
)
LaTeX Font Info: Trying to load font information for U+txmia on input
line 1
70.
(c:/texlive/2024/texmf-dist/tex/latex/txfonts/utxmia.fd
File: utxmia.fd 2000/12/15 v3.1
)
LaTeX Font Info: Trying to load font information for U+msa on input
line 170
.
(c:/texlive/2024/texmf-dist/tex/latex/amsfonts/umsa.fd
File: umsa.fd 2013/01/14 v3.01 AMS symbols A
)
LaTeX Font Info: Trying to load font information for U+msb on input
line 170
.
(c:/texlive/2024/texmf-dist/tex/latex/amsfonts/umsb.fd
File: umsb.fd 2013/01/14 v3.01 AMS symbols B
)
LaTeX Font Info: Trying to load font information for U+txsync on input
line 1
70.
(c:/texlive/2024/texmf-dist/tex/latex/txfonts/utxsync.fd
File: utxsync.fd 2000/12/15 v3.1
)

Package natbib Warning: Citation `richter2016playing' on page 2 undefined
on in
put line 173.

Package natbib Warning: Citation `lecun2002gradient' on page 2 undefined
on inp
ut line 173.

Package natbib Warning: Citation `ganin2015unsupervised' on page 2
undefined on
input line 175.

```

Package natbib Warning: Citation `goodfellow2014generative' on page 2  
undefined  
on input line 175.

Package natbib Warning: Citation `zou2018unsupervised' on page 2  
undefined on i  
nput line 175.

[2]  
<figure1.png, id=77, 838.63312pt x 504.38437pt>  
File: figure1.png Graphic file (type png)  
<use figure1.png>  
Package pdftex.def Info: figure1.png used on input line 179.  
(pdftex.def) Requested size: 172.5pt x 103.74579pt.

Package natbib Warning: Citation `ganea2018hyperbolic' on page 3  
undefined on i  
nput line 184.

Package natbib Warning: Citation `nickel2017poincare' on page 3 undefined  
on in  
put line 184.

Package natbib Warning: Citation `krioukov2010hyperbolic' on page 3  
undefined o  
n input line 184.

Package natbib Warning: Citation `khrulkov2020hyperbolic' on page 3  
undefined o  
n input line 184.

Package natbib Warning: Citation `atigh2022hyperbolic' on page 3  
undefined on i  
nput line 184.

[3 <./figure1.png>  
Overfull \hbox (55.70862pt too wide) in paragraph at lines 188--189  
[]\T1/lmr/m/n/10 We con-duct ex-ten-sive ex-per-i-ments on stan-dard  
bench-mark  
s, in-clud-ing GTA5\TS1/lmr/m/n/10 ^^Y\T1/lmr/m/n/10 Cityscapes  
[]

Package natbib Warning: Citation `hoffman2018cycada' on page 4 undefined on input line 194.

Package natbib Warning: Citation `li2019bidirectional' on page 4 undefined on input line 194.

Package natbib Warning: Citation `ma2022i2f' on page 4 undefined on input line 194.

Package natbib Warning: Citation `ma2022i2f' on page 4 undefined on input line 194.

Package natbib Warning: Citation `hoffman2016fcns' on page 4 undefined on input line 194.

Package natbib Warning: Citation `tsai2018learning' on page 4 undefined on input line 194.

Package natbib Warning: Citation `chen2018road' on page 4 undefined on input line 194.

Package natbib Warning: Citation `ganin2015unsupervised' on page 4 undefined on input line 194.

[4]

Package natbib Warning: Citation `zou2018unsupervised' on page 5 undefined on input line 196.

Package natbib Warning: Citation `zou2019confidence' on page 5 undefined on input line 196.

Package natbib Warning: Citation `mei2020instance' on page 5 undefined on input line 196.

Package natbib Warning: Citation `li2019bidirectional' on page 5 undefined on input line 196.

Package natbib Warning: Citation `mukherjee2020uncertainty' on page 5 undefined on input line 196.

[5]

Package natbib Warning: Citation `zou2018unsupervised' on page 6 undefined on input line 198.

Package natbib Warning: Citation `long2015learning' on page 6 undefined on input line 198.

Package natbib Warning: Citation `tsai2018learning' on page 6 undefined on input line 198.

Package natbib Warning: Citation `tsai2018learning' on page 6 undefined on input line 198.

Package natbib Warning: Citation `lin2017focal' on page 6 undefined on input line 198.

Package natbib Warning: Citation `hoyer2022daformer' on page 6 undefined on input line 198.

Underfull \hbox (badness 10000) in paragraph at lines 198--200

[]

Package natbib Warning: Citation `nickel2017poincare' on page 6 undefined  
on in  
put line 201.

Package natbib Warning: Citation `sala2018representation' on page 6  
undefined o  
n input line 201.

Package natbib Warning: Citation `ganea2018hyperbolic' on page 6  
undefined on i  
nput line 201.

Package natbib Warning: Citation `nickel2017poincare' on page 6 undefined  
on in  
put line 201.

[6]

Package natbib Warning: Citation `khrulkov2020hyperbolic' on page 7  
undefined o  
n input line 203.

Package natbib Warning: Citation `dhall2020hierarchical' on page 7  
undefined on  
input line 203.

Package natbib Warning: Citation `liu2020hyperbolic' on page 7 undefined  
on inp  
ut line 203.

Package natbib Warning: Citation `weng2021unsupervised' on page 7  
undefined on  
input line 203.

Package natbib Warning: Citation `atigh2022hyperbolic' on page 7  
undefined on i  
nput line 203.

Package natbib Warning: Citation `ganea2018hyperbolic' on page 7  
undefined on i  
nput line 203.

Package natbib Warning: Citation `weng2021unsupervised' on page 7  
undefined on  
input line 205.

Package natbib Warning: Citation `atigh2022hyperbolic' on page 7  
undefined on i  
nput line 205.

Package natbib Warning: Citation `ganea2018hyperbolic' on page 7  
undefined on i  
nput line 205.

[7]

Package natbib Warning: Citation `halo2021hyperbolic' on page 8 undefined  
on in  
put line 207.

<figure2a.png, id=106, 1198.4775pt x 459.21562pt>  
File: figure2a.png Graphic file (type png)  
<use figure2a.png>  
Package pdftex.def Info: figure2a.png used on input line 223.  
(pdftex.def) Requested size: 310.4979pt x 118.9658pt.  
<figure2b.png, id=107, 710.655pt x 272.01625pt>  
File: figure2b.png Graphic file (type png)  
<use figure2b.png>  
Package pdftex.def Info: figure2b.png used on input line 230.  
(pdftex.def) Requested size: 207.0021pt x 79.23134pt.

LaTeX Warning: `h' float specifier changed to `ht'.

[8{c:/texlive/2024/texmf-dist/fonts/enc/dvips/lm/lm-  
mathit.enc}{c:/texlive/2024  
/texmf-dist/fonts/enc/dvips/lm/lm-mathsy.enc}]

[9 <./figure2a.png> <./figure2b.png>]

[10]

Package natbib Warning: Citation `nickel2017poincare' on page 11  
undefined on i  
nput line 252.

Package natbib Warning: Citation `dol1976riemannian' on page 11 undefined  
on inp  
ut line 254.

```
[11{c:/texlive/2024/texmf-dist/fonts/enc/dvips/lm/lm-  
rm.enc}{c:/texlive/2024/te  
xmf-dist/fonts/enc/dvips/lm/lm-mathex.enc}]
```

Package natbib Warning: Citation `atigh2022hyperbolic' on page 12  
undefined on  
input line 273.

Package natbib Warning: Citation `ganea2018hyperbolic' on page 12  
undefined on  
input line 273.

[12]

[13]

Package natbib Warning: Citation `tranheden2021dacs' on page 14 undefined  
on in  
put line 315.

Package hyperref Info: bookmark level for unknown algorithm defaults to 0  
on in  
put line 318.

Underfull \hbox (badness 10000) in paragraph at lines 335--336  
[ ] \T1/lmr/m/n/10 Gen-er-ate pseudo-labels (per-pixel): \$\OML/lmm/m/it/10  
p[ ] \  
OT1/lmr/m/n/10 =  
[ ]

Underfull \hbox (badness 2538) in paragraph at lines 341--342  
[ ] \T1/lmr/m/n/10 Com-pute the source do-main losses for  
\$\OMS/lmsy/m/n/10 f\OM  
L/lmm/m/it/10 x[]; y[]\OMS/lmsy/m/n/10 g\$\T1/lmr/m/n/10 :  
\$\OMS/lmsy/m/n/10 L[]  
\OML/lmm/m/it/10 ; \OMS/lmsy/m/n/10 L[]  
[ ]

[14]

[15]

[16]

[17]

Overfull \hbox (42.80386pt too wide) detected at line 418



[][][][][]  
[]

[18]

Package natbib Warning: Citation `cordts2016cityscapes' on page 19  
undefined on  
input line 445.

Package natbib Warning: Citation `richter2016playing' on page 19  
undefined on i  
nput line 445.

Package natbib Warning: Citation `ros2016synthia' on page 19 undefined on  
input  
line 445.

Overfull \hbox (7.7084pt too wide) in paragraph at lines 447--448  
\T1/lmr/m/n/10 19 shared cat-e-gories are used for train-ing and eval-u-  
a-tion  
in the GTAV\TS1/lmr/m/n/10 ^^Y\T1/lmr/m/n/10 Cityscapes  
[]

[19]

Package natbib Warning: Citation `contributors2023mmsegmentation' on page  
20 un  
defined on input line 451.

Package natbib Warning: Citation `hoyer2022daformer' on page 20 undefined  
on in  
put line 451.

Package natbib Warning: Citation `xie2021segformer' on page 20 undefined  
on inp  
ut line 451.

Package natbib Warning: Citation `chen2018encoder' on page 20 undefined  
on inpu  
t line 451.

Package natbib Warning: Citation `he2016deep' on page 20 undefined on  
input lin

e 451.

Package natbib Warning: Citation `hoyer2022daformer' on page 20 undefined  
on in  
put line 453.

Package natbib Warning: Citation `hoyer2022daformer' on page 20 undefined  
on in  
put line 453.

Package natbib Warning: Citation `tranheden2021dacs' on page 20 undefined  
on in  
put line 453.

Package natbib Warning: Citation `atigh2022hyperbolic' on page 20  
undefined on  
input line 453.

Package natbib Warning: Citation `halo2021hyperbolic' on page 20  
undefined on i  
nput line 453.

[20]  
LaTeX Font Info: External font `lmex10' loaded for size  
(Font) <9> on input line 463.  
LaTeX Font Info: External font `lmex10' loaded for size  
(Font) <6> on input line 463.

Overfull \hbox (5.22267pt too wide) in paragraph at lines 495--496  
[]|\T1/lmr/bx/n/7 mIoU|  
[]

Package natbib Warning: Citation `tsai2018learning' on page 21 undefined  
on inp  
ut line 500.

Package natbib Warning: Citation `zou2018unsupervised' on page 21  
undefined on  
input line 501.

Package natbib Warning: Citation `luo2019taking' on page 21 undefined on  
input  
line 502.

Package natbib Warning: Citation `wang2020classes' on page 21 undefined on input line 503.

Package natbib Warning: Citation `zhang2021prototypical' on page 21 undefined on input line 504.

Package natbib Warning: Citation `hoyer2022daformer' on page 21 undefined on input line 505.

Package natbib Warning: Citation `zhao2023learning' on page 21 undefined on input line 506.

Package natbib Warning: Citation `ma2022i2f' on page 21 undefined on input line 507.

Package natbib Warning: Citation `li2022feature' on page 21 undefined on input line 508.

Package natbib Warning: Citation `zhu2025hard' on page 21 undefined on input line 509.

Overfull \hbox (98.7046pt too wide) in paragraph at lines 470--514  
[[  
[

LaTeX Warning: `h' float specifier changed to `ht'.

Overfull \hbox (5.22267pt too wide) in paragraph at lines 552--553  
[|T1/lmr/bx/n/7 mIoU|  
[

Package natbib Warning: Citation `tsai2018learning' on page 21 undefined on input line 557.

Package natbib Warning: Citation `zou2018unsupervised' on page 21  
undefined on  
input line 558.

Package natbib Warning: Citation `luo2019taking' on page 21 undefined on  
input  
line 559.

Package natbib Warning: Citation `wang2020classes' on page 21 undefined  
on input  
line 560.

Package natbib Warning: Citation `zhang2021prototypical' on page 21  
undefined on  
input line 561.

Package natbib Warning: Citation `hoyer2022daformer' on page 21 undefined  
on input  
line 562.

Package natbib Warning: Citation `zhao2023learning' on page 21 undefined  
on input  
line 563.

Package natbib Warning: Citation `ma2022i2f' on page 21 undefined on  
input line  
564.

Package natbib Warning: Citation `li2022feature' on page 21 undefined on  
input  
line 565.

Package natbib Warning: Citation `zhu2025hard' on page 21 undefined on  
input line  
566.

Overfull \hbox (98.7046pt too wide) in paragraph at lines 527--571  
[] []  
[]

LaTeX Warning: `h' float specifier changed to `ht'.

[21]

[22]

LaTeX Warning: `h' float specifier changed to `ht'.

[23]

```
<figure3.png, id=240, 5204.44376pt x 2516.40125pt>
File: figure3.png Graphic file (type png)
<use figure3.png>
Package pdftex.def Info: figure3.png used on input line 605.
(pdfteX.def) Requested size: 172.5pt x 83.39859pt.
```

[24 <./figure3.png>]

```
<figure4a.png, id=249, 1615.53563pt x 1598.22093pt>
File: figure4a.png Graphic file (type png)
<use figure4a.png>
Package pdftex.def Info: figure4a.png used on input line 619.
(pdfteX.def) Requested size: 117.29874pt x 116.03265pt.
<figure4b.png, id=250, 1661.45718pt x 1606.50188pt>
File: figure4b.png Graphic file (type png)
<use figure4b.png>
Package pdftex.def Info: figure4b.png used on input line 625.
(pdfteX.def) Requested size: 120.7521pt x 116.75642pt.
```

[25 <./figure4a.png> <./figure4b.png>]

```
<figure5a1.png, id=265, 513.92pt x 256.96pt>
File: figure5a1.png Graphic file (type png)
<use figure5a1.png>
Package pdftex.def Info: figure5a1.png used on input line 644.
(pdfteX.def) Requested size: 65.55084pt x 32.7747pt.
<figure5b1.png, id=266, 513.92pt x 256.96pt>
File: figure5b1.png Graphic file (type png)
<use figure5b1.png>
Package pdftex.def Info: figure5b1.png used on input line 649.
(pdfteX.def) Requested size: 65.55084pt x 32.7747pt.
<figure5c1.png, id=267, 513.92pt x 256.96pt>
File: figure5c1.png Graphic file (type png)
<use figure5c1.png>
Package pdftex.def Info: figure5c1.png used on input line 654.
(pdfteX.def) Requested size: 65.55084pt x 32.7747pt.
<figure5d1.png, id=268, 513.92pt x 256.96pt>
File: figure5d1.png Graphic file (type png)
<use figure5d1.png>
Package pdftex.def Info: figure5d1.png used on input line 660.
(pdfteX.def) Requested size: 65.55084pt x 32.7747pt.
<figure5e1.png, id=269, 512.91624pt x 256.96pt>
File: figure5e1.png Graphic file (type png)
<use figure5e1.png>
Package pdftex.def Info: figure5e1.png used on input line 666.
```

```

(pdftex.def) Requested size: 65.55084pt x 32.83743pt.
<figure5a2.png, id=270, 513.92pt x 256.96pt>
File: figure5a2.png Graphic file (type png)
<use figure5a2.png>
Package pdftex.def Info: figure5a2.png used on input line 676.
(pdftex.def) Requested size: 65.55084pt x 32.7747pt.
<figure5b2.png, id=271, 511.9125pt x 256.96pt>
File: figure5b2.png Graphic file (type png)
<use figure5b2.png>
Package pdftex.def Info: figure5b2.png used on input line 682.
(pdftex.def) Requested size: 65.55084pt x 32.90408pt.
<figure5c2.png, id=272, 513.92pt x 256.96pt>
File: figure5c2.png Graphic file (type png)
<use figure5c2.png>
Package pdftex.def Info: figure5c2.png used on input line 688.
(pdftex.def) Requested size: 65.55084pt x 32.7747pt.
<figure5d2.png, id=273, 513.92pt x 256.96pt>
File: figure5d2.png Graphic file (type png)
<use figure5d2.png>
Package pdftex.def Info: figure5d2.png used on input line 694.
(pdftex.def) Requested size: 65.55084pt x 32.7747pt.
<figure5e2.png, id=274, 513.92pt x 255.95625pt>
File: figure5e2.png Graphic file (type png)
<use figure5e2.png>
Package pdftex.def Info: figure5e2.png used on input line 700.
(pdftex.def) Requested size: 65.55084pt x 32.64667pt.
<figure5a3.png, id=275, 513.92pt x 256.96pt>
File: figure5a3.png Graphic file (type png)
<use figure5a3.png>
Package pdftex.def Info: figure5a3.png used on input line 710.
(pdftex.def) Requested size: 65.55084pt x 32.7747pt.
<figure5b3.png, id=276, 512.91624pt x 256.96pt>
File: figure5b3.png Graphic file (type png)
<use figure5b3.png>
Package pdftex.def Info: figure5b3.png used on input line 717.
(pdftex.def) Requested size: 65.55084pt x 32.83743pt.
<figure5c3.png, id=277, 513.92pt x 256.96pt>
File: figure5c3.png Graphic file (type png)
<use figure5c3.png>
Package pdftex.def Info: figure5c3.png used on input line 724.
(pdftex.def) Requested size: 65.55084pt x 32.7747pt.
<figure5d3.png, id=278, 510.90875pt x 256.96pt>
File: figure5d3.png Graphic file (type png)
<use figure5d3.png>
Package pdftex.def Info: figure5d3.png used on input line 731.
(pdftex.def) Requested size: 65.55084pt x 32.96683pt.
<figure5e3.png, id=279, 513.92pt x 256.96pt>
File: figure5e3.png Graphic file (type png)
<use figure5e3.png>
Package pdftex.def Info: figure5e3.png used on input line 738.
(pdftex.def) Requested size: 65.55084pt x 32.7747pt.

```

Package natbib Warning: Citation `atigh2022hyperbolic' on page 26 undefined on

input line 747.

[26]

LaTeX Warning: File `figure6a.png' not found on input line 755.

! Package pdftex.def Error: File `figure6a.png' not found: using draft setting.

See the pdftex.def package documentation for explanation.  
Type H <return> for immediate help.

...

1.755 ...eight=5cm, keepaspectratio]{figure6a.png}

Try typing <return> to proceed.  
If that doesn't work, type X <return> to quit.

LaTeX Font Info: Trying to load font information for T1+lm-tt on input  
line 7  
55.

(c:/texlive/2024/texmf-dist/tex/latex/lm/t1lmtt.fd  
File: t1lmtt.fd 2015/05/01 v1.6.1 Font defs for Latin Modern  
)

LaTeX Warning: File `figure6b.png' not found on input line 762.

! Package pdftex.def Error: File `figure6b.png' not found: using draft setting.

See the pdftex.def package documentation for explanation.  
Type H <return> for immediate help.

...

1.762 ...eight=5cm, keepaspectratio]{figure6b.png}

Try typing <return> to proceed.  
If that doesn't work, type X <return> to quit.

LaTeX Warning: `h' float specifier changed to `ht'.

[27 <./figure5a1.png (PNG copy)> <./figure5b1.png> <./figure5c1.png>  
<./figure5  
d1.png> <./figure5e1.png> <./figure5a2.png (PNG copy)> <./figure5b2.png>  
<./fig

```
ure5c2.png> <./figure5d2.png> <./figure5e2.png> <./figure5a3.png (PNG
copy)> <./figure5b3.png> <./figure5c3.png> <./figure5d3.png> <./figure5e3.png>]
```

[28]

[29]

Package natbib Warning: Citation `halo2021hyperbolic' on page 30  
undefined on input line 833.

[30]

[31]

No file "Manuscript ".bbl.

Package natbib Warning: There were undefined citations.

[32] (./Manuscript .aux)

\*\*\*\*\*

LaTeX2e <2024-06-01> patch level 2

L3 programming layer <2024-05-27>

\*\*\*\*\*

Package rerunfilecheck Info: File `Manuscript ".out' has not changed.

(rerunfilecheck) Checksum:

1EA37B4EDABA565569D4956D760E665D;2409.

)

Here is how much of TeX's memory you used:

14371 strings out of 473583

222173 string characters out of 5732343

2013908 words of memory out of 5000000

36918 multiletter control sequences out of 15000+600000

661751 words of font info for 108 fonts, out of 8000000 for 9000

1141 hyphenation exceptions out of 8191

75i,12n,79p,2090b,579s stack positions out of

10000i,1000n,20000p,200000b,200000s

<c:/texlive/2024/texmf-

dist/fonts/typel/public/lm/lmbx10.pfb><c:/texlive/2024

/texmf-dist/fonts/typel/public/lm/lmbx5.pfb><c:/texlive/2024/texmf-

dist/fonts/t

ypel/public/lm/lmbx7.pfb><c:/texlive/2024/texmf-

dist/fonts/typel/public/lm/lmbx

9.pfb><c:/texlive/2024/texmf-

dist/fonts/typel/public/lm/lmex10.pfb><c:/texlive/

2024/texmf-dist/fonts/typel/public/lm/lmmi10.pfb><c:/texlive/2024/texmf-

dist/fo

nts/typel/public/lm/lmmi5.pfb><c:/texlive/2024/texmf-

dist/fonts/typel/public/lm



```
/lmmi6.pfb><c:/texlive/2024/texmf-  
dist/fonts/type1/public/lm/lmmi7.pfb><c:/texl  
ive/2024/texmf-  
dist/fonts/type1/public/lm/lmr10.pfb><c:/texlive/2024/texmf-dist  
/fonts/type1/public/lm/lmr12.pfb><c:/texlive/2024/texmf-  
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dist/fonts/type1/public/lm/lmri8.pfb><c:/t  
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blic/lm/lmsy7.pfb><c:/texlive/2024/texmf-  
dist/fonts/type1/public/lm/lmsy9.pfb><  
c:/texlive/2024/texmf-  
dist/fonts/type1/public/lm/lmtt10.pfb><c:/texlive/2024/te  
xmfb-  
dist/fonts/type1/public/amsfonts/symbols/msam5.pfb><c:/texlive/2024/texmf  
-d  
ist/fonts/type1/public/amsfonts/symbols/msbm10.pfb>  
Output written on "Manuscript .pdf" (32 pages, 5281877 bytes).  
PDF statistics:  
483 PDF objects out of 1000 (max. 8388607)  
344 compressed objects within 4 object streams  
81 named destinations out of 1000 (max. 500000)  
218 words of extra memory for PDF output out of 10000 (max. 10000000)
```



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**Declaration of interests**

☒The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: