
January 17, 2026

RE: Revision 1 to Manuscript ID COIN-SA-11-24-10097 for Consideration of Computational Intelligence

Dear Dr. Inkpen and Reviewers,

We would like to thank you for your careful evaluation of our manuscript. It is our pleasure to inform you that we have considered the received comments and carefully addressed them in the manuscript as indicated below. We believe these revisions have strengthened the manuscript and addressed the reviewers' comments, and hope that the revised version meets the expectations of the editor and reviewers. We would like to highlight some important points summarily:

- We clarified the experimental setup, including detailed explanations of metric calculations via illustrative examples. We expanded the experimental evaluation to include the recommended team size of top- $k = 5$ and an additional significance level of $\alpha = 0.05$. To ensure robustness and reproducibility, we reran the original experiments. We further extended the analysis of the results, providing deeper insights into the observed findings and clearer attribution of outcomes.
- We improved the use of terminology and notation across the manuscript. This includes resolving variable name conflicts, harmonizing symbols, and refining definitions to ensure precision and readability throughout the paper. To strengthen the theoretical foundation and improve clarity, we added 5 new equations, 2 propositions, 1 definition, and 7 illustrative examples. These additions are intended to better illustrate the notions of fairness in the team recommendation task, as well as the assumptions and implications underlying both the proposed and baseline reranking methods.
- We expanded the citations by adding more than 15 new works, including pioneering and standard references in the literature, as well as very recent studies, with particular emphasis on fairness in team recommendation systems.

Cordially,
The authors.

REVIEWER 1

Pros

- The paper tackles the significant issue of fairness in team recommendation.
- The proposed method is practical and relatively simple, suggesting broad applicability.
- The paper is well-written, self-contained, and logically structured.
- The experiments are well-executed, and the paper acknowledges the limitations of the proposed approach.

Cons

The main concerns revolve around a lack of clarity in several sections and confusing notation (see required revisions). Specifically:

- The definitions of group fairness for neural recommendation are unclear.
- It is not evident how these definitions are measured in the experiments or how they relate to the evaluation metrics (ndkl, skew, and exposure).
- The novelty and effectiveness of the proposed method appear marginal.
- The reliability of the results on popularity bias is questionable due to the definition of popularity.
- The paper's contribution would be more impactful if it effectively addressed gender bias, a more prevalent source of bias.

Response: We sincerely thank you for the thorough and constructive feedback. In the following, we provide detailed responses, having carefully considered all the points raised, and the manuscript has been revised accordingly.

R1.1

The paper should justify why popularity is treated as a protected attribute, similar to gender. Discuss the subjective nature of popularity, its potential correlation with expertise, and whether it should be considered a biased feature rather than a protected one.

Response: Thank you for your comment. We have added a new Section **3.3.1 Protected Attribute and Group** with two subsections **Gender as a Canonical Protected Attribute** and **Popularity as an Unconventional Protected Attribute** in **3.3 Fair Team Recommendation**, to formally define (social) groups and their associated protected attributes, and to examine whether popularity can be considered as a protected attribute, discussing its nuances relative to canonical protected attributes like gender. We further moved the subsections **Popularity Labels** and **Gender Labels** from Section **4.1 Dataset Labeling Criteria** to this section to provide a more coherent and integrated discussion, and to avoid sporadic treatment of experts' labeling criteria for their protected attributes across the manuscript.

Revised Text:

3.3.1 Protected Attribute and Group

"We define a (social) group \mathcal{G} as a subset of the experts \mathcal{E} that shares an "identity trait"¹, which may be inherent to an expert and largely immutable [...]

Gender as a Canonical Protected Attribute: *In this paper, given the protected attribute $A:\text{gender}$, the values = $\{a : \text{female}, a' : \text{male}\}$ create disjoint protected groups of experts including female experts $\mathcal{G}_{a:\text{female}}$ and male experts $\mathcal{G}_{a':\text{male}}$ where [...]*

Popularity as an Unconventional Protected Attribute: *As highlighted by Gallegos et al. and others^{1,2}, a group can also be formed based on an identity trait that is contextual, e.g., disability, dynamic, e.g., religion, or socially constructed based on social network effects and historical contingencies, like outcomes or conditions that arise from past events, as in popularity^{3,4,5}. However, [...]*

R1.2

Provide relevant citations for each group fairness definition on Page 6, Lines 12, 32, and 52.

Response: Thank you for your suggestion. We have revised the manuscript with citations, including seminal works that pioneered this line of research and have since become standard references in the literature, as follows:

⁶ Dwork C, Hardt M, Pitassi T, Reingold O, Zemel RS. Fairness through awareness. In: Goldwasser S., ed. Innovations in Theoretical Computer Science 2012, Cambridge, MA, USA, January 8-10, 2012ACM 2012:214–226841. <https://dl.acm.org/doi/10.1145/2090236.2090255>.

⁷ Hardt M, Price E, Srebro N. Equality of Opportunity in Supervised Learning. In: Advances in Neural Information Processing Systems, Barcelona, Spain 2016:3315–3323. <https://proceedings.neurips.cc/paper/2016/hash/9d2682367c3935defcb1f9e247a97c0d-Abstract.html>.

⁸ Altenburger KM, De R, Frazier K, Avteniev N, Hamilton J. Are There Gender Differences in Professional Self-Promotion? An Empirical Case Study of LinkedIn Profiles Among Recent MBA Graduates. In: AAAI Press 2017:460–463.839. <https://doi.org/10.1609/icwsm.v11i1.14929>.

¹ Gallegos IO, Rossi RA, Barrow J, et al. Bias and Fairness in Large Language Models: A Survey. *Comput. Linguistics*. 2024;50(3):1097–1179. https://doi.org/10.1162/coml_a_00524.

⁹ John PG, Vijaykeerthy D, Saha D. Verifying Individual Fairness in Machine Learning Models. In: Proceedings of the Thirty-Sixth Conference on Uncertainty in Artificial Intelligence, UAI 2020, virtual online, August 3-6, 2020. <http://proceedings.mlr.press/v124/george-john20a.html>.

¹⁰ Zehlike M, Yang K, Stoyanovich J. Fairness in Ranking, Part I: Score-Based Ranking. *ACM Comput. Surv.* 2023;55(6):118:1–118:36. <https://doi.org/10.1145/3533379>.

¹¹ Rosenblatt L, Witter RT. Counterfactual Fairness Is Basically Demographic Parity. In: Thirty-Seventh AAAI Conference on Artificial Intelligence, AAAI 2023, Washington, DC, USA, February 7-14, 2023:14461–14469. <https://doi.org/10.1609/aaai.v37i12.26691>.

¹² Ashurst C, Weller A. Fairness Without Demographic Data: A Survey of Approaches. In: ACM 2023:14:1–14:12722. <https://doi.org/10.1145/3617694.3623234>.

¹³ Romano Y, Bates S, Candès EJ. Achieving Equalized Odds by Resampling Sensitive Attributes. In: Larochelle H, Ranzato M, Hadsell R, Balcan M, Lin H., eds. Advances in Neural Information Processing Systems 33: Annual Conference on Neural Information Processing Systems 2020, NeurIPS 2020, December 6-12, 2020, virtual 2020. <https://proceedings.neurips.cc/paper/2020/hash/03593ce517feac573fdafa6dcedef61-Abstract.html>.

Revised Text:

3.3 Fair Team Recommendation

“To eschew varied interpretations and to provide actionable criteria to design and evaluate fairness-aware algorithms, fairness has been mathematically formalized, with a level of abstraction from an underlying real-world scenario, based on well-known notions of justice and equity at an individual level^{9,10}, or at a group level^{1,7,8,6} like female vs. male experts [...]”

3.3.2 Demographic Parity

“Demographic (statistical) parity is to provide equal treatment to protected groups, i.e., the proportion of individuals receiving a favorable outcome should be consistent across all protected groups according to their distribution in the population^{14,11,12}. [...]”

3.3.3 Equalized Odds

“Equalized odds^{7,13} is a stronger notion of fairness. [...]”

3.3.4 Equal Opportunity

“Equal opportunity is a relaxed version of equalized odds that only requires fairness for the desired ground-truth decision, that is, the ‘opportunity’⁷. ”

R1.3

Correct the typo "equalized odds" on Page 6, Line 55.

Response: We apologize for the oversight. We have proofread the manuscript and fixed this typo as well as others:

"[...] based on the equalized *dds* [...]" → "[...] based on the equalized *odds* [...]"

"*equality of opportunity*" → "*equal opportunity*"

"[...] items with small *probability* [...]" → "[...] items with small *probabilities*]"

"*these values adjusted closer to the ideal.*" → "*these values were adjusted closer to the ideal.*"

Also, because groups are formed based on a protected attribute, all resulting groups are, by definition, protected. To differentiate groups, we revised the manuscript to consistently use the terms by '*disadvantaged*' vs. '*advantaged*' groups in place of '*protected*' vs. '*non-protected*' groups. Accordingly,

"*protected group*" → "*disadvantaged group*"

"*nonprotected group*" → "*advantaged group*"

"*disadvantaged protected group*" → "*disadvantaged group*"

Moreover, to avoid the naming conflict between p , which denotes probability throughout the manuscript (e.g., $p(e \in E)$), and the Bernoulli winning probability p used in **Section 3.4 Proposed Probabilistic Reranking Method**, we rename the latter to q . Accordingly,

$$\mathbb{F}^{-1}(\alpha; k, \textcolor{red}{p}) \rightarrow \mathbb{F}^{-1}(\alpha; k, \textcolor{blue}{q})$$

R1.4

Clarify the notation in Equations 4 through 8. Specifically, define d and \hat{d} to depend on the given expert (i or j). Also, consistently define e_0 and e_1 (whether they refer to group membership or experts).

Response: Thank you for your comment. We agree that our original formalization included unnecessary notation, such as variable enumerators (e.g., i or j) and confusing subscript conventions. We have revised the formal definitions to use simpler, clearer, and more consistent notation, while remaining mathematically sound to the best of our knowledge. For instance, we adopt a consistent convention of using a prime (' \prime ') to distinguish different protected groups, avoiding subscript enumerators, where distinct values a and a' of the protected attribute \mathcal{A} define the groups \mathcal{G}_a and $\mathcal{G}_{a'}$, respectively. Also, for an expert in a group based on her/his value of protected attribute, we use explicit notation of group membership $e \in \mathcal{G}_a$ or $e \in \mathcal{G}_{a'}$ to prevent the confusion by subscript enumeration. Accordingly, we revised Equations 9 to 19. For more clarity, we also added Examples 1, 2, and 3 for each fairness notions as well as a comprehensive running Example 4 with new Tables 1 and 2 to illustrate how both fairness notions and accuracy are measured. Please also refer to our response to R1.6.

R1.5

Clarify Equation 9. Can a definition of fairness be binary? Address the possibility of achieving absolute zero disparity for equal opportunity and demographic parity. Specify any threshold used to consider Equations 5 and 8 as satisfied and explain how this threshold was chosen.

Response: Thank you for the question. Prior work, including Dwork et al.⁶, defines notions of fairness based on pairwise distribution differences among protected groups, often up to a bias threshold ϵ : "*Definition 3.1 (Statistical parity). We say that a mapping $M : V \rightarrow \delta(A)$ satisfies statistical parity between distributions S and T up to bias ϵ if [...].*" In our work, we assume a zero bias, i.e., $\epsilon = 0$, for all notions of fairness. This allows for a direct comparison of prior and posterior distributions using

well-known fairness metrics such as `skew` and `ndk1`. To make this clearer, we have added Propositions 2 and 3, which form the basis for calculating fairness metrics. Equation 9 has been revised (now Equation 23) to explicitly reference these propositions. Additionally, we have included illustrative examples for each notion of fairness, demonstrating when zero disparity can be achieved. A comprehensive running Example 4 in Tables 1 and 2 further shows cases of zero disparity and otherwise for the considered notions of fairness.

In our experiments, fairness metrics quantify the divergence of the posterior distributions of protected groups in a recommended team from their prior distributions and report the *average* across the *test* set. Zero disparity corresponds to exact equality between posterior and prior distributions for each protected group in *every* recommended team, yielding 0 for both metrics; though this is rarely achieved in practice. Otherwise, these metrics report the divergence, with values closer to 0 indicating fairer outcomes. No additional thresholding was applied; the metrics directly reflect the degree of disparity.

R1.6

Address the confusing notation on Line 43. If y (used in the fairness definition with $d = 1$ and $d = 0$ as ground truth) is different from d , clarify their relationship and how the fairness definitions handle both.

Response: Thank you for your comment. We agree that the original formalization contained confusing notation. We have revised the manuscript as follows:

1. We moved the discussion of **Success Labels** from Section 4.1 Dataset Labeling Criteria to Section 3.1 Preliminaries by introducing a new Section 3.2 Successful Teams, to provide a more coherent and integrated treatment of the success label y used in neural team recommendation models. We clarified that in the absence of explicit labels for unsuccessful teams, neural team recommenders presume all instances of teams in the training dataset are successful (positive samples) for their observable outcomes, e.g., *published* papers in dblp, that is, $\mathcal{T} = \mathcal{T}^+ = \{(S, E)_{y=1}\}$ and proceed with the training procedure. As a result, during the inference, for an input required set of skill S , the models predict (recommend) a subset of experts E for a successful team only, and throughout the paper, the act of recommending a team is understood as recommending a potentially successful team $(S, E)_y \rightarrow (S, E)_{y=1}$.
2. In Section 3.3.3 Equalized Odds, we clarified how the ground-truth decision d is defined and mapped to expert qualification with respect to the required skill set S of a recommended team. Specifically, when an expert's skill set has a non-empty intersection with S , i.e., $S_e \cap S \neq \emptyset$, the ground-truth decision is $d = e \in E$. Accordingly, we removed the binary values $\{0, 1\}$ previously used for d and revised the decision space to $d \in \mathcal{D} = \{e \in E, e \notin E\}$.
3. For additional clarity, in Section 3.3.5 A Fair Team, we added a comprehensive running Example 4 with new Tables 1 and 2 to illustrate how both fairness notions and accuracy are measured. The example explicitly demonstrates the trade-offs between different fairness criteria and predictive accuracy.

Revised Text:

3.2Successful Teams

“From Definition 1 and 2, neural team recommenders aim at estimating f from samples of teams that are labeled with success or failure, yet most available training data in team recommendation literature only consists of successful teams, missing unsuccessful ones [...]”

3.3.2 Demographic Parity

Example 1. *“Consider a set of $|\mathcal{E}| = 100$ experts, where \mathcal{A} denotes gender, and $|\mathcal{G}_{a:\text{female}}| = 30$ and $|\mathcal{G}_{a':\text{male}}| = 70$ represent the groups of female and male experts, respectively. Suppose we want to recommend a team of size $k = 10$ for a required set of skills S , i.e., $(S, E)_{y=1}$. To satisfy demographic parity, [...]”*

3.3.3 Equalized Odds

Example 2. *“From Example 1, for a set of $|\mathcal{E}| = 100$ experts, where \mathcal{A} denotes gender, $|\mathcal{G}_{a:\text{female}}| = 30$ and $|\mathcal{G}_{a':\text{male}}| = 70$ represent female and male groups, respectively. To recommend a fair team of size $k = 10$ for a required set of skills S , we first identify the qualified and unqualified experts. Suppose there are 10 female and 10 male experts whose skill sets intersect with S*

(i.e., qualified experts), and the remaining 20 female and 60 male experts are not qualified. To satisfy equalized odds, [...]"

3.3.4 Equal Opportunity

Example 3. "Referring to our earlier Example 2 with a set of $|\mathcal{E}| = 100$ experts, where \mathcal{A} denotes gender, and $|\mathcal{G}_{a:\text{female}}| = 30$ and $|\mathcal{G}_{a':\text{male}}| = 70$ represent female and male groups, respectively, we aim to recommend a fair team of size $k = 10$ for a required set of skills S . To satisfy equal opportunity, [...]"

3.3.5 A Fair Team

Example 4. "To illustrate the evaluation of fairness and accuracy in recommended teams, we consider a small population of 6 experts, where two are female $\mathcal{G}_{a:\text{female}} = \{\boxed{e_1}, \boxed{e_2}\}$ and 4 are male $\mathcal{G}_{a':\text{male}} = \{e_3, e_4, e_5, e_6\}$. The required skill set for a successful team is $S = \{s_1, s_2\}$, and only a subset of experts is qualified, i.e., their skill sets intersect with S [...]"

R1.7

On Line 30, when comparing with pre-processing methods, acknowledge that pre-processing methods are also model-agnostic. Update the statement to emphasize that the proposed method's distinction lies solely in its post-training nature.

Response: Thank you for the clarification. We have revised the manuscript in **1 Introduction** and **2.2 Fairness-aware Recommendation** and acknowledge that pre-processing methods are also model-agnostic. However, we further explain the post-processing advantages over pre-processing, including (1) less demand for computing resources^{15,16}; pre-processing mid to large-scale training datasets is costly, (2) more privacy preserving^{17,18}; no direct access to the raw data is required, and (3) more practically feasible in the era of pretrained models.

Revised Text:

1 Introduction "[...] As opposed to pre-processing-based methods¹⁹, which, despite being model-agnostic, require direct access to raw and potentially sensitive training data^{18,17} along with substantial computational resources to modify the data or its labels prior to model training^{15,16}, or in-processing techniques^{20,21,22}, which are model-dependent and focus on balancing model accuracy with fairness considerations during training, our method belongs to post-processing category of methods, which are simple and computationally efficient by improving the fairness of model's outputs after training, without adjustments.[...]"

2.2 Fairness-aware Team Recommendation

"[...] The latter category is of particular interest due to several practical advantages. Foremost, post-processing methods are computationally efficient, as they do not require access to or manipulation of raw training data, which are typically medium- to large-scale, unlike pre-processing or in-processing methods^{15,16}. Secondly, post-processing methods can be readily plugged into already trained and deployed models without retraining or fine-tuning, a scenario that is increasingly common in realistic settings where pre-processing or in-processing interventions are infeasible. Finally, post-processing methods are more privacy-preserving, as they do not require access to potentially sensitive raw training data, as in pre-processing methods, nor the architecture or parameters of private models, as in in-processing methods^{17,18}. [...]”

R1.8

Explain why the Bayesian Neural Network (BNN) architecture (Figure 3) is preferable for neural team recommendation compared to a standard Multi-Layer Perceptron (MLP), beyond simply motivating its use.

Response: Thank you for the suggestion. We revised Section **3.1 Preliminaries** and explained that Bayesian neural networks estimate prior uncertainty of model parameters $p(\theta)$ via maximum a posteriori, whereas standard multilayer perceptron overlooks it and hence results in overconfident estimates of model parameters. We further include prior studies in which standard multilayer

perceptrons (non-variational feedforward neural networks) are employed as baselines to demonstrate the performance gains of variational neural networks.

Revised Text:

“During training, given a team (S, E) , neural models tune the parameters θ by maximizing the posterior probability of θ in f_θ over \mathcal{T} . From Bayes theorem:

$$\operatorname{argmax}_\theta p(\theta|\mathcal{T}) \propto p(\mathcal{T}|\theta)p(\theta) = p(\theta) \prod_{(S, E) \in \mathcal{T}} p(E|S, \theta) \quad (1)$$

$$p(E|S, \theta) = \prod_{j \in e} \sigma(z[j]) \propto \sum_{j \in e} \log \sigma(z[j]) \quad (2)$$

where $p(\mathcal{T}|\theta)$ is the likelihood and $p(\theta)$ is the prior joint probability of weights, which is unknown. While the exact prior probability of weights $p(\theta)$ cannot be calculated analytically²³, it can be estimated as Gaussian distributions by a variational Bayesian neural architecture via the maximum a posteriori optimization^{24,25,26}, which contrasts with conventional non-variational multilayer perceptron that assume a uniform probability distribution over all possible real-values of θ and only estimate the likelihood $p(\mathcal{T}|\theta)$ via maximum likelihood optimization, discarding prior uncertainty $p(\theta)$, and hence, resulting in overconfident point estimates of θ ²³. Existing studies primarily adopt standard multilayer perceptrons (non-variational feedforward neural networks) as baselines to demonstrate the performance advantages of variational neural networks^{27,28,23}.

R1.9

On Line 39 and throughout the experiments, clearly explain how the metrics ndkl, skew, and exposure are used to measure demographic parity and equal opportunity.

Response: Thank you for pointing this out. We have added Propositions 2 in Section 3.3.2 Demographic Parity and Proposition 3 in Section 3.3.4 Equal Opportunity to formalize the rationale on measuring fairness as post-hoc manner after reranking based on the prior distribution as reference distribution: demographic parity uses the group distributions in the full expert set, while equality of opportunity uses the group distributions among qualified experts. The metrics measure deviations between the reranked posterior distributions and the prior distributions of groups. We have further added Examples 5, 6, and 7 in Section 4.4.3 Fairness and Utility Metrics, for more clarification.

Revised Text:

“Normalized Discounted KL Divergence (ndkl) [...]”

Example 5. [...] Using the same top-10 ranking, suppose 3 female experts in positions {2, 5, 9}. Using demographic parity, the reference distribution is $p(e \in G_{a:\text{female}}) = \frac{30}{100} = 0.3$, and at top-2, one female expert appears, yielding the posterior distribution $q_2 = \frac{1}{2} = 0.5$, and the KL-divergence ($p||q_2$) is therefore positive; $k_1(p||q_2) = p(e \in G_{a:\text{female}}) \times \log \frac{p(e \in G_{a:\text{female}})}{q_2(a)} + p(e \in G_{a':\text{male}}) \times \log \frac{p(e \in G_{a':\text{male}})}{q_2(a')} = 0.3 \times \log(\frac{0.3}{0.5}) + 0.7 \times \log(\frac{0.7}{0.5}) = 0.081 [...]”$

“Skew@k [...]”

Example 6. [...] Same as Example 5, using the same top-10 ranking where 3 female experts appear at positions {2, 5, 9}, reference distribution under demographic parity is $p(e \in G_{a:\text{female}}) = \frac{30}{100} = 0.30$, and the posterior distribution for a protected expert in cutoff top-2, top-5 and top-10 are $q_2 = \frac{1}{2} = 0.5$, $q_5 = \frac{2}{5} = 0.4$ and $q_{10} = \frac{3}{10} = 0.3$, respectively. The the resulting skew@2= $\log \frac{q_2}{p} = \log(\frac{0.5}{0.3}) = 0.511$, skew@5= $\log \frac{q_5}{p} = \log(\frac{0.4}{0.3}) = 0.288$, and skew@10= $\log \frac{q_{10}}{p} = \log(\frac{0.3}{0.3}) = 0$. In other words, skew@k captures the magnitude of representation imbalance at a given cutoff, but unlike ndkl, it overlooks positional importance within the ranking [...]”

“Utility-aware Exposure (expo)[...”]

Example 7. [...] We continue with the same top-10 ranking as in Examples 5 and 6, where 3 female experts appear at positions

$\{2, 5, 9\}$. Suppose that the output probabilities (utilities) assigned by a team recommendation model to these experts are 0.95, 0.80 and 0.65, respectively. Exposure assigns higher importance to earlier positions in the ranking through a position-based weighting function. By Equation 34 the average exposure of the female experts is $\mu_{\text{expo}}(a : \text{female}) = \frac{1}{3}(\frac{1}{\log 3} + \frac{1}{\log 6} + \frac{1}{\log 10}) = 0.634. [...]”$

R1.10

Given that protected attributes are often inferred, clarify in the discussion that the absence of ground truth labels or the use of inferred values might lead to over- or under-estimation of bias, cite references [1, 2].

[1] Chen, J., Kallus, N., Mao, X., Svacha, G., & Udell, M. (2019, January). Fairness under unawareness: Assessing disparity when protected class is unobserved. In *Proceedings of the conference on fairness, accountability, and transparency* (pp. 339-348)

[2] Kenfack, P. J., Kahou, S. E., & Aïvodji, U. (2024). A survey on fairness without demographics. *Transactions on Machine Learning Research*. 2024

Response: Thank you for this observation. We have added a clarification in Section **3.3.1 Protected Attribute and Group** and Section **4.2 Forming Protected Groups** to acknowledge that when protected attributes are inferred rather than directly observed, they may inherently incorporate societal biases, and we have cited the suggested references. We also moved Section **4 Ethical Considerations** to Section **4.2 Forming Protected Groups** to highlight this concern by examples.

Revised Text:

3.3.1 Protected Attribute and Group

Gender as a Canonical Protected Attribute: [...] It is worth noting that, when gender values are inferred rather than directly observed, they may inherently incorporate societal biases, or even amplify pre-existing stereotypes in society^{29,30}, as further illustrated by examples in our experimental setup (Section 4.2). Therefore, fairness assessments and bias mitigation using these inferred values may over- or under-estimate disparities across groups, and results should be interpreted with this limitation in mind. [...]”

4.2 Forming Protected Groups

[...] Meanwhile, we recognize that predicting gender using name-to-gender services such as genderize might systematically mislabel certain demographic groups due to cultural, linguistic, and regional variations. For example, names such as ‘Andrea’ (typically male in Italy but female in English-speaking countries), ‘Sasha’ (male in Russia but commonly female in North America), and ‘Kim’ (gender-neutral in East Asia but often inferred as female in Western countries) are frequently misclassified. Hence, our results should be interpreted with this limitation in mind.[...]"

R1.11

On Line 51, Page 3, clarify the difference between "bnn" and "bnn-emb".

Response: Thank you for your comment. We have revised Section **3.1 Preliminaries** and added the new **Definition 2 Neural Team Recommendation** to further clarify on Bayesian neural network architecture and explicitly enumerate alternative choices for skill representations at the input layer, including occurrence vectors and dense embeddings, and contrast their properties, explaining why dense embeddings are the preferable choice. Also, in **4.3.1 Neural Team Recommendation**, where we explain the baseline methods, we remind readers of the Section **3.1 Preliminaries** for further details.

Revised Text:

*“**Definition 2 (Neural Team Recommendation).** Given a subset of skills S and all teams \mathcal{T} as the training set, neural team recommendation estimates $f_\theta(S)$ using a multilayer neural network that learns, from \mathcal{T} , to map a vector representation of subset*

of skills S , referred to as v_S , to a vector representation of subset of experts E , referred to as v_E , by maximizing the posterior probability of θ in f_θ over \mathcal{T} , that is, $\text{argmax}_\theta p(\theta|\mathcal{T})$.

For the vector representation of subset of skills v_S , neural team recommendation methods adopt either

1. The occurrence vector representation for S , which is a Boolean vector of size $|S|$, i.e., $v_S \in \{0, 1\}^{|S|}$ where $v_S[s] = 1$ if $s \in S$, and 0 otherwise, or
2. The embedding representation of S , which is a dense low d -dimensional vector, $d << |S|$, pretrained by e.g., a shallow neural encoder²⁵ like in distributional representation of words (word2vec)³¹ and documents (doc2vec)³², or a graph neural network^{33,26}.

While occurrence vector representations are simple, they lead to high-dimensional sparse input representations, substantially increasing the number of trainable parameters in the input layer of neural networks. In contrast, dense pretrained vectors (embeddings) provide low-dimensional, continuous representations that significantly reduce model complexity and enable more stable and data-efficient learning. Moreover, dense embeddings capture latent semantic relationships among skills, allowing the model to generalize across similar inputs rather than treating each skill as independent, as is the case with the occurrence representation.”

4.2.1 Neural Team Recommendation

“For the input layer, as detailed in Section 3.1, we used [...]”

R1.12

On Line 3, Page 3, replace higher is better (should ↑)".

Response: Thank you for raising this error. We have fixed the issue in the caption of Tables 14, 10 and 12.

R1.13

Explain why other re-ranking methods, such as ‘det-cons’, are more successful in mitigating gender bias while the proposed method is not. Discuss potential trade-offs between fairness and accuracy and how interventions can manage this trade-off.

Response: Thank you for your valuable comment. We have added the details of our baseline models to Section 4.3.2 Fairness-aware Reranking to demonstrate why the deterministic methods outperform our method in fairness but at the cost of utility.

R1.14

On Line 11, Page 10, justify the choice of $\alpha = 0.1$ and explain or provide experiments on how different values of p and α affect the fairness-accuracy performance.

Response: Thank you for this comment. Foremost, we acknowledge the variable naming conflict between p , which denotes probability throughout the manuscript (e.g., $p(e \in E)$), and the Bernoulli winning probability p used in Section 3.4 Proposed Probabilistic Reranking Method. In the revised manuscript, we renamed the latter to q , accordingly. Moreover, we added Examples 1 and 3 and revised Table 3 with additional rows to explain how different values of q have been selected based on the notions of fairness. For demographic parity, by Proposition 2, q is set to the prior distribution of disadvantaged experts in the full dataset, and for equal opportunity, by Proposition 3, q is set per test team (S, E) as the proportion of disadvantaged qualified experts among those qualified for the required skill set S . Therefore, while q can technically be varied over the interval $[0, 1]$, it has been set based on notions of fairness, as opposed to a tunable hyperparameter.

Regarding the role of the significance level α , as explained in Section 3.4 Proposed Probabilistic Reranking Method, a top- k recommended team is considered fair if the number of experts from the disadvantaged group, denoted $|E|_a$ is consistent

with a Bernoulli process with success probability q , where q is set according to a specified notion of fairness. We denote this distribution by $\mathbb{F}(\mathbb{E}\ell_a; k, q)$. For example, as shown in Table 3, under demographic parity with $q = 0.3$ and $k = 10$, the expected number of experts from the disadvantaged group in the team is $0.3 \times 10 = 3$. Suppose an observed recommendation contains x such experts. We then conduct a significance test with the null hypothesis

$$H_0 : x \sim \mathbb{F}(x; k = 10, q = 0.3)$$

and compute the corresponding p -value under this distribution. If the p -value exceeds a predefined significance level α , the observation is considered statistically plausible under H_0 , and we “fail to reject” the null hypothesis, treating the team as fair. Conversely, if the p -value is less than or equal to α , the observation is deemed unlikely, leading to rejection of H_0 and the team being flagged as *unfair*. As seen, the choice of α directly controls the strictness of the fairness criterion. Larger values of α increase the likelihood of rejecting H_0 , requiring stronger alignment with the distribution. For instance, when $\alpha = 0.1$ and no disadvantaged experts are observed ($x = 0$) in a top- $k = 10$, the p -value is $\mathbb{F}(x = 0; k = 10, q = 0.3) = 0.028 < 0.1$, and the null hypothesis is rejected, flagging the team as *unfair*. In contrast, for $\alpha = 0.01$, the same observation yields $0.028 > 0.01$, and the null hypothesis is not rejected, resulting in the team being considered fair. From a mitigation perspective, larger values of α impose stricter fairness requirements, as more disadvantaged experts are needed for a team to pass the significance test. Smaller values of α relax this requirement and may not trigger mitigation even when the observed composition deviates from the expected proportion. This behavior is illustrated in Table 3 for $\alpha \in \{0.5, 0.1, 0.05, 0.01\}$. Hence, larger values of α are preferable when the goal is to actively enforce fairness constraints.

In response to this comment, (1) we have clarified the role and effect of α in the revised manuscript in **Section 3.4 Proposed Probabilistic Reranking Method**, accordingly. (2) In addition to the originally reported results with $\alpha = 0.1$, we have added new experiments with $\alpha = 0.05$, which is commonly used in statistical hypothesis testing (e.g., paired t -tests for average performance comparisons). The new results, reported in Tables 14, 10, and 12, exhibit consistent fairness–accuracy trade-offs across $\alpha \in \{0.1, 0.05\}$.

Revised Text:

3.4 Proposed Probabilistic Reranking Method

“[...] Regarding the role of the significance level α , suppose an observed recommendation contains x experts from the disadvantaged group. We perform a significance test with the null hypothesis $H_0 : x \sim \mathbb{F}(x; k = 10, q = 0.3)$ and compute the corresponding p -value. If the p -value $> \alpha$, the observation is considered statistically plausible under H_0 , and we therefore “fail to reject” the null hypothesis, treating the team as fair. Conversely, if the p -value $\leq \alpha$, the observation is deemed unlikely, leading to rejection of H_0 and the team being flagged as *unfair*. The choice of α directly controls the strictness of the fairness criterion. Larger values of α increase the likelihood of rejecting H_0 , requiring stronger alignment with the distribution. For instance, when $\alpha = 0.1$ and no disadvantaged experts are observed ($x = 0$) in a top- $k = 10$, the p -value is $\mathbb{F}(x = 0; k = 10, q = 0.3) = 0.028 < 0.1$, and the null hypothesis is rejected, flagging the team as *unfair*. In contrast, for $\alpha = 0.01$, the same observation yields $0.028 > 0.01$, and the null hypothesis is not rejected, resulting in the team being considered fair. From a mitigation perspective, larger values of α impose stricter fairness requirements, as more disadvantaged experts are needed for a team to pass the significance test. Smaller values of α relax this requirement and may not trigger mitigation even when the observed composition deviates from the expected proportion, as shown in Table 3 for $\alpha \in \{0.50, 0.1, 0.05, 0.01\}$. Meanwhile, the choice of α also controls the fairness trade-off with accuracy of the recommended experts (utility), allowing more conservative (e.g., $\alpha = 0.1$) vs. permissive ($\alpha = 0.5$) additions of experts from the disadvantaged group by avoiding unnecessary enforcement of proportion constraints and reducing utility loss while maintaining statistically grounded fairness.[...]"

R1.15

In Table 6, explain why the exposure before fairness intervention for gender is already close to 1, despite skewness in gender representation suggesting female experts should receive lower exposure and utility.

Response:

R1.16

On Page 8, clarify why the proposed method might not select more qualified female experts to achieve the desired fairness, especially given the assumption of at least k experts from each protected group (Line 34). Explain why the method might avoid selecting experts from disadvantaged groups even when their desired proportion is not met in the current top- i iteration. If the greedy method does prioritize female experts to meet the desired proportion, explain how the proposed method enforces the evaluation fairness metrics (refer back to point 9).

Response: Thank you for this comment. We acknowledge that the original manuscript did not clearly explain the probabilistic nature of our method, especially the role of null hypothesis testing with a significance level α , which may have caused confusion. We have clarified this in our responses to R1.13, R1.14, and R2.5, and revised Sections **3.4 Proposed Probabilistic Reranking Method** and **4.3.2 Fairness-aware Reranking**, accordingly. We hope these revisions clarify the concern raised here. Specifically, in reply to R1.14, we detailed the role of the significance level and explained how fairness is ensured via a statistical significance test as opposed to strict selections of experts based on lower and upper bounds in deterministic reranker baselines. Our method calculates the required number of disadvantaged experts (e.g., females) at each top- k such that the observed number of disadvantaged experts in the top- k follows, statistically and significantly, given a significance level α , the binomial distribution of independent Bernoulli trials with winning probability q , which is set based on the underlying notion of fairness. As long as the observed count of disadvantaged experts passes the significance test ($p\text{-value} > \alpha$), the ranking is treated as fair, even if the target proportion is not strictly met at that particular prefix.

Moreover, in reply to [REDACTED] and Reviewer 2's comment [REDACTED], we explain limitations of deterministic baselines: (1) they may force the selection of additional experts from disadvantaged group even when the fairness constraint is already satisfied, making such selections unnecessary; and (2) when the disadvantaged group is also a minority group (e.g., female experts), this over-enforcement can lead to a drop in utility; and (3) very small prior representation for a disadvantaged group in imbalanced datasets can skew fairness evaluation, as deterministic methods may remove already included disadvantaged members to align the posterior distribution strictly with the prior.

We also revised the manuscript to a more accurate assumption of having at least $k \times p(e \in \mathcal{G}_a)$ experts from the disadvantaged group for demographic parity fairness, ensuring that the prior group distribution matches its posterior distribution among the top- k recommended experts for a successful team (Proposition 2), and $k \times p(e \in \mathcal{G}_a \mid S_e \cap S \neq \emptyset)$ qualified from the disadvantaged group for equal opportunity fairness, so that the prior distribution of qualified experts matches its posterior distribution among the top- k recommendations for a successful team (Proposition 3).

Revised Text:

3.4 Proposed Probabilistic Reranking Method

[...] Regarding the role of the significance level α , suppose an observed recommendation contains x experts from the disadvantaged group. We perform a significance test with the null hypothesis $H_0 : x \sim \mathbb{F}(x; k = 10, q = 0.3)$ and [...]”

[...] To form a fair ranking of k experts, we assume there exist at least ~~k members from each protected group~~ $k \times q$ experts from the disadvantaged group. To satisfy demographic parity, we require $k \times p(e \in \mathcal{G}_a)$ experts from the disadvantaged group, ensuring that the prior group distribution matches its posterior distribution among the top- k recommended experts for a successful team (Proposition 2). To satisfy equal opportunity, we require $k \times p(e \in \mathcal{G}_a \mid S_e \cap S \neq \emptyset)$ qualified from the disadvantaged group, so that the prior distribution of qualified experts matches its posterior distribution among the top- k recommendations for a successful team (Proposition 3).[...]"

4.3.2 Fairness-aware Reranking

[...] In contrast to deterministic methods that enforce hard minimum and maximum constraints at each prefix, our method achieves fairness through distributional alignment using a significant level, which maintains the desired fairness notions while reducing utility loss by avoiding the forced inclusion of disadvantaged experts when it is not necessary. [...]”

REVIEWER 2

This paper addresses the fairness problem in neural team recommendation systems. They suggest a post-processing model-agnostic reranking technique to address this problem. In this regard, they utilized three datasets in three distinct types of team recommendation tasks, illustrating how their method can mitigate existing biases against protected groups. The protected attributes in this work are popularity and gender. While their reranking mechanism works well in case of popularity bias, it falls short in addressing gender bias. To demonstrate the effectiveness of their work, they evaluated its impact against three deterministic reranking methods on various fairness metrics, including skew, ndkl and expo. To assess the effect of probabilistic reranking on utility, they utilized information retrieval metrics, including map and ndcg.

Strength:

- It is well-written, easy to follow, and understand.
- The problem is a critical yet underexplored issue concerning fairness, and this work offers a promising suggestion to address the existing bias in the system.
- The problem is well-defined and well-formalized.
- Fairness measures for evaluation and improvement are clearly defined and explained.
- Utility metrics have been used to show the fairness-utility trade-offs.
- Multiple datasets have been utilized for evaluation to avoid reliance on a single task or dataset.

Response: We are grateful for your careful reading and constructive feedback. We appreciate the positive evaluation of the clarity, problem formulation, and the experimental setup, as well as the recognition of the importance of addressing fairness in team recommendation systems.

R2.1

While mentioning the existence of other probability-based reranking methods, such as the one by Zehlike et al. [93], they did not use it as a baseline that is more similar to their approach, nor did they explain why it has not been used.

Response: We appreciate you pointing this out. We would like to clarify that our probabilistic method builds upon and adapts the framework of Zehlike et al.³⁴ for the team recommendation task, introducing several necessary modifications. Specifically, our approach generalizes the item-level ranking to team compositions, incorporates team-level success probabilities, which are not present in the original formulation, and alters the reranking procedure. As a result, the original method of Zehlike et al. cannot serve as a separate baseline, since it is effectively a special case of our team-level adaptation. We have revised the manuscript to clarify this point in multiple places, including the **Abstract**, **1 Introduction**, **2.2 Fairness-aware Team Recommendation**, and **4.3.2 Fairness-aware Reranking** sections, making the lineage and novelty of our method explicit while being transparent about the connection to Zehlike et al.'s work³⁴.

Revised Text:

Abstract

[...] *Inspired by the promising performance of probabilistic rerankers in user-item recommender systems for fairness guarantees, we further propose develop a probabilistic greedy reranking algorithm [...]*

1 Introduction

[...] *Specifically, building upon the promising performance of probabilistic reranking methods for fair user-item recommendation, we propose develop a probabilistic fairness-aware reranking method to [...]*

2 Related Work

2.2 Fairness-aware Team Recommendation

[...] *To the best of our knowledge, there is yet to be a neural team recommendation method that specifically takes fairness into account except Loghmani et al.³⁵, wherein the application of deterministic reranking algorithms³⁶ to mitigate popularity bias in neural team recommenders^{25,24,27} were shown futile due to the substantial compromise to the models' accuracy. Building upon*

Zehlike et al.³⁴'s work, we adapt a probabilistic reranking method for the team recommendation task. However, unlike item-level ranking in their work, team recommendation requires rankings of experts for a team compositions while enforcing fairness over the team as a whole. Our method incorporates team-level success probabilities instead, which is absent in Zehlike et al."

4.3.2 Fairness-aware Reranking

Our fairness-aware reranking baselines include three deterministic greedy reranking algorithms *det-greedy*, *det-cons*, and *det-relaxed* by Geyik et al.³⁶ as well as our proposed probabilistic reranking method with the significance level $\alpha=0.10$ and 0.05 . Our probabilistic method builds upon the framework of Zehlike et al.³⁴ and adapts it for the team recommendation task, introducing necessary modifications to handle team compositions by altering the reranking procedure. Consequently, the original method cannot serve as a separate baseline, as it is effectively a trivial special case of our team-level adaptation."

R2.2

While equalized odds has also been defined as a notion of group metric, it has not been used to evaluate the suggested algorithm, and the justification provided for this is unconvincing. (That we only care about qualified members of the protected group). While non-qualified members of a non-protected group receive positive decisions, their protected counterparts should be treated similarly.

Response: We thank the reviewer for raising this point. Our decision to omit evaluating equalized odds is not to disregard unqualified experts, but rather based on the team recommendation optimization during training. In our setting, positive decisions for unqualified experts correspond to false positives, which are explicitly penalized by the training objective (Section 3.1 Preliminaries and Definition 2 Neural Team Recommendation), and later evaluated by utility metrics, as recommending unqualified experts degrades team utility. Consequently, such outcomes are already discouraged by the model. Enforcing parity (fairness) over these undesirable outcomes, as required by equalized odds, is therefore redundant and may conflict with the recommendation objective. For instance, in our running example in Table 2, all candidate recommended teams consist of qualified experts, except row #4, which includes the unqualified expert e_5 and decreases the accuracy metric. Such outcomes are already penalized during training. Ensuring that unqualified experts are also equally distributed across protected groups is an unnecessarily strong and practically misaligned constraint, particularly given that well-performing recommenders avoid recommending unqualified experts. Similar considerations have been studied in other predictive modeling settings^{37,38,39}. From Tang and Zhang³⁷,

"It has been shown that if base rates of positives differ among groups, then Equalized Odds and Predictive Rate Parity cannot be achieved simultaneously for non-perfect predictors^{38,39}. Any two out of three among Demographic Parity, Equalized Odds, and Predictive Rate Parity are incompatible with each other⁴⁰."

We have clarified this rationale in the revised manuscript in Section 3.3.5 A Fair Team:

"While equalized odds is a more comprehensive notion of fairness by enforcing parity not only among qualified experts, as in equal opportunity, but also among unqualified experts for the favorable decision of being in a recommended successful team, we do not adopt it in this work. In the context of team recommendation, enforcing parity over unqualified experts is redundant and misaligned with the recommendation objective, wherein models are explicitly trained to identify qualified experts from the required skill set S , and unqualified experts are penalized by the learning objective, as discussed in Section 3.1 and Definition 2. Consequently, outcomes involving unqualified experts are already controlled downstream by the model during training. This observation has also been studied in other predictive models^{37,38,39,40}, leading to the adoption of equal opportunity as a more focused and actionable fairness notion."

R2.3

Results are presented for top-k = 100 (as per Section 4.2.1), and the study lacks an evaluation of its methodology concerning various values of k.

Response: We apologize for the confusion and acknowledge that our use of the values 100 and 10 for k was unclear. We discuss this together with the comment in R2.4 below.

R2.4

According to the dataset definitions, the actual team sizes in the datasets are small (between 1.88 and 3.06). To achieve a more reliable evaluation of the method, it would have been preferable to use these team sizes (or various team sizes) for evaluation. As per section 4.3.1, they used $k=10$ (which, however, differs from $k=100$ as mentioned in 4.2.1). I suggest providing more clarification on these other values of k and the team sizes used.

Response: We apologize for the confusion and acknowledge that our use of the values 100 and 10 for k was unclear. In our experiments, we actually used two different cut-offs, serving distinct purposes. The first cut-off is an internal parameter used purely for computational efficiency in code execution. It limits the expert pool by only the top-K probabilities from the neural model in the last layer (Equation) and reduces memory usage. The neural model outputs a probability for each expert in the expert pool $|\mathcal{E}|$. Given a test set of size $|test|$, storing all probabilities would require a large matrix of $|\mathcal{E}| \times |test|$. For memory and storage efficiency for the underlying reranking methods, we did a first-stage retrieval (best practice in Information Retrieval systems); For each test team, we rank the probabilities once and retain only the top-K=100, which yields a manageable matrix of size $100 \times |test|$. This step is a common practice for efficiency in such systems and was not intended to be mentioned in the manuscript. However, at the reviewer's request, we can add a brief explanation of the first-stage cut-off of $K=100$ applied to the predicted probabilities. The second cut-off, denoted as k , is the central experimental parameter, representing the final recommended team size and the focus of our evaluation. Unfortunately, the similarity in the roles of these two cut-offs led to confusion, and the value 100 reported in the paper should have been 10 and associated with k . We have revised the manuscript to correct this issue.

Regarding the top- $k=10$, as the final recommended team of size k (second cut-off), although the average team size in the datasets is small (between 1.88 and 3.06), applying fairness-aware reranking at such small cardinalities can lead to over- or underestimation of the actual fairness metrics. For example, if the desired ratio between female and male experts is 0.3:0.7, then for a team of size 2 this corresponds to 0.6 female and 1.4 male members. The only feasible integer splits are (0 female, 2 male) or (1 female, 1 male), yielding ratios of 0 or 0.5, which deviate substantially from the target 0.3 and can result in large inaccuracies when reporting fairness metrics. Similarly, for a team of size 3, the expected split is 0.9 and 2.1, with feasible splits (0 female, 3 male) or (1 female, 2 male), giving a ratio of approximately 0.33. As shown, using a larger k allows more accurate calculation of posterior distributions and reduces rounding errors and large deviations. On the other hand, as noted, real-world teams are often of size 2–3 members. To balance the need for meaningful posterior calculation with real-world team sizes, we therefore adopt $k=10$ as the primary evaluation setting, where, for example, $0.3 \times 10 = 3$ female and $0.7 \times 10 = 7$ male members can be exactly realized. We have clarified this rationale in Section 4.3.1 Neural Team Recommendation.

Finally, in response to the reviewer's suggestion to evaluate additional team sizes, we have extended the revised manuscript to include results for $k=5$ in Tables *, *, and *, which exhibit consistent trends as in $k=10$.

Revised Text:

4.3.1 Neural Team Recommendation

“[...] Given a team (S, E) from the test set, we select the top- $k \in \{5, 10\}$ experts with the highest probabilities as the recommended team $E = f_\theta(S)$ by the model of each fold. Although the average team size in the datasets is small (between 1.88 and 3.06), evaluating fairness-aware reranking at such small cardinalities can lead to over- or underestimation of the fairness metrics. For example, if the desired ratio between female and male experts is 0.3 to 0.7, then for a team of size $k=2$, this corresponds to 0.6 female and 1.4 male members and feasible splits are either (0 female, 2 male) or (1 female, 1 male), yielding ratios of 0 or 0.5 and deviates substantially from the target 0.3. Hence, it can result in large inaccuracies when reporting fairness metrics. Similarly, for a team of size 3, the expected split is 0.9 and 2.1, with feasible splits (0 female, 3 male) or (1 female, 2 male), giving a ratio of approximately 0.33. As shown, using a larger k allows for a more accurate calculation of posterior distributions and reduces rounding errors and large deviations. On the other hand, as noted, real-world teams are often of size 2 to 3 members. To balance the need for meaningful posterior calculation with real-world team sizes, we therefore adopt top- $k \in \{5, 10\}$ [...]”

4.4.1 Before Mitigating Bias

[...] report the average performance of models on all folds in terms of information retrieval metrics including mean average precision (map) and normalized discounted cumulative gain ($ndcg$) at top- $k \in \{5, 10\}$ =10, as explained in Section 4.4.3.[...]"

R2.5

According to the results presented, with the fixed setting used to evaluate the effect of their method on mitigating bias against unpopular individuals and women, their method is successful in reducing popularity bias but fails to address gender bias. While gender bias is more important to mitigate (according to the works in the literature, popularity bias is not always a real bias), why should this method be used when it fails to address more critical biases? As justification for this shortcoming, the authors cited the significant gender bias as a reason for the probabilistic reranking technique's failure to mitigate said bias, as it lacks qualified female candidates to select from. This makes it even more crucial to address, because while smaller biases need to be mitigated, addressing bigger ones is even more vital. However, the results indicate that even in circumstances such as demographic parity in dplp, where females are overrepresented, applying this technique can create a negative bias against them, resulting in underrepresentation. To address this issue, the authors proposed employing in-processing techniques as future work. While one key contribution of this work is its model-agnostic approach using a post-processing technique, it is essential to ensure that there are no effective in-processing fairness techniques in place first.

Response:

R2.6

While Table 6 indicates that the authors concluded the effectiveness of their technique across all metrics and datasets, it should be taken into account that in certain cases (for imdb, gender bias, equity of opportunity for both baselines, and demographic parity for bnn-emp, as well as uspt for gender and demographic parity) this method even increased bias, and the improvements in other cases are marginal.

Response:

R2.7

The order of protected and non-protected groups in Table 5 differs from that in Tables 3 and 4; it is better to maintain the same order to make the tables more readable.

Response: Thank you for bringing this error to our attention. We have corrected the ordering of the disadvantaged (**protected**) and disadvantaged (**nonprotected**) groups in all result tables to ensure consistency.

ARTICLE TYPE

A Probabilistic Greedy Attempt to be Fair in Neural Team Recommendation

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Abstract

Neural team recommendation has brought state-of-the-art efficacy while enhancing efficiency at forming teams of experts whose success in completing complex tasks is almost surely guaranteed; ~~albeit~~ However, they overlook fairness, that is, predicted teams are heavily biased toward popular and male experts, falling short of recommending *female* or *nonpopular* experts. In this work, we introduce and formalize the *fair team recommendation* problem in view of group-based notions of fairness. Inspired by the promising performance of probabilistic rerankers in user-item recommender systems for fairness guarantees, we further propose develop a probabilistic greedy reranking algorithm to achieve fairness with respect to popularity or gender biases in neural models with respect to different notions of fairness, including *demographic parity* and *equal opportunity*. Specifically, we aim to ensure a minimum representation of experts from the disadvantaged nonpopular or female groups by reranking the neural model's ranked list of recommended experts. Our experiments on three large-scale benchmark datasets demonstrate: (1) neural team recommenders heavily suffer from biases toward popular and male experts; (2) our reranking method can substantially mitigate such biases while maintaining teams' efficacy; (3) in the presence of extreme biases, post-processing reranking methods alone fall short, urging further tandem integration of pre-process and in-process debiasing techniques. The code to reproduce the experiments reported in this paper is available at <https://github.com/fani-lab/Adila> <https://github.com/fani-lab/Adila/tree/coin25>.

KEY WORDS

Fair Team Recommendation, Neural Team Recommendation, Social Information Retrieval.

1 | INTRODUCTION

As modern tasks have surpassed the capacity of individuals, forming teams of experts whose collaboration for a common goal yields success has been a surge of research interest in many disciplines, including psychology^{41,42}, the science of team science (SciTS)⁴³, and industrial engineering⁴⁴. Forming teams can be seen as social information retrieval (Social IR) where the right group of experts are searched and hired to solve the task at hand. Traditionally, teams were formed manually by relying on human experience and instinct; a tedious, error-prone, and suboptimal process for an overwhelming number of experts, a multitude of objectives to optimize (e.g., budget, time and team size constraints), and hidden personal and societal biases, among other reasons. As a result, a rich body of various computational methods, from operations research^{45,46,47,48,49,50,51,52,53,54,55}, social network analysis^{56,57,58,59}, and recently, machine learning^{60,61,25,27,62,63,64,65,26,24,66,67,68,69} have been proposed. Specifically, neural models learn the distributions of experts and their skill sets in the context of successful and unsuccessful teams from training datasets to recommend future teams that are *almost surely* successful. Such models have brought state-of-the-art efficacy while enhancing efficiency, taking the stage and becoming canonical in team recommendation literature.

The primary focus of existing team recommenders is, however, the maximization of the models' accuracy (utility), largely ignoring the fairness in their ranked list of recommended experts, leading to discrimination, reduced visibility for already disadvantaged experts, and gender disparities^{70,34,71}. These unfair biases, far from being random, originate mainly from training datasets. As seen in Figure 1, such datasets are segmented toward *male* experts, and *females* are heavily under-represented, like

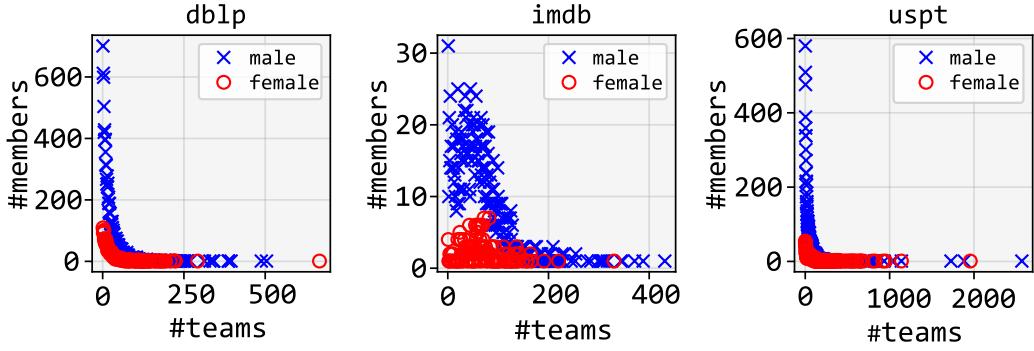


FIGURE 1 Distribution of experts in terms of gender in dblp, imdb, and uspt datasets.

in the dblp dataset of computer research articles with %86 male vs. %14 female researchers. Also, from Figure 2, datasets in team recommendation suffer from popularity bias; that is, the majority of nonpopular experts have scarcely participated in the (successful) teams, whereas a few popular experts dominates many teams. Therefore, popular or male experts would receive more attention and are more frequently recommended by a machine learning model, leading to systematic discrimination against already disadvantaged nonpopular or female experts. To the best of our knowledge, there is no fairness-aware approach in neural team recommendation methods except that of Loghmani et al.³⁵, who applied deterministic greedy reranking algorithms to mitigate popularity bias and showed such deterministic methods can mitigate bias but at the cost of a substantial drop in the models' accuracy.

In this paper, foremost, we introduce and formalize the *fair team recommendation* problem to foster standards and conventions, which the literature on the team recommendation problem lacks. We set forth a unified set of notations to define the problem in view of group-based notions of fairness, including demographic (statistical) parity^{72,14,11,12}, equalized odds^{7,73,13,37,74}, and equality-of opportunity^{7,75}. We further incorporate the notions of fairness in tandem with experts' skills in team recommendations to facilitate recommending merit-based teams while ~~equal~~fair opportunity is also maximized. Specifically, ~~building upon the promising performance of probabilistic reranking methods for fair user-item recommendation, we proposed~~ develop a probabilistic fairness-aware *reranking* method to adjust the ordering of experts in the final ranked list of recommended experts to address potential biases and promote fairness concerning gender or popularity biases. ~~As opposed to pre-processing-based methods, which modify data or its labels before model training, or in-processing techniques, which focus on balancing model accuracy with fairness considerations during training, our method is model agnostic and belongs to post-processing category of methods, which seek to improve the fairness of model's outputs after training, without adjustments to the data, training procedure, or the model's architecture~~ As opposed to pre-processing-based methods^{76,77,78,19}, which, despite being model-agnostic, require direct access to raw and potentially sensitive training data^{18,17} along with substantial computational resources to modify the data or its labels prior to model training^{15,16}, or in-processing techniques^{79,80,20,21,22,81}, which are model-dependent and focus on balancing model accuracy with fairness considerations during training, our method belongs to *post-processing* category of methods^{82,83,34,84,85,22,36,86}, which are simple and computationally efficient by improving the fairness of model's outputs after training, without adjustments to the data, training procedure, or the model's architecture. Moreover, being probabilistic, our approach holds advantages over deterministic methods for managing real-world uncertainties. Instead of providing rigid decisions, our approach offers distributions over possible outcomes, resulting in more adaptive solutions. To illustrate the effectiveness of our proposed approach, we perform experiments on three large-scale benchmark datasets of computer science articles (dblp)^{87,58}, moving pictures (imdb)^{88,56}, and US patents (uspt)⁸⁹. Our results show that our proposed approach substantially mitigates popularity bias while maintaining the success rate of the recommended teams. With respect to gender bias, however, our approach's impact has been marginal due to the highly sparse distribution of female experts in the training datasets (%14, %12, and %14 in dblp, imdb and uspt, respectively), urging further future studies on integration of pre-process and in-process debiasing techniques.

In summary, our key contributions are as follows:

1. We defined the problem of fair team recommendation in view of group-based notions of fairness including demographic (statistical) parity, equalized odds, and equality-of opportunity.

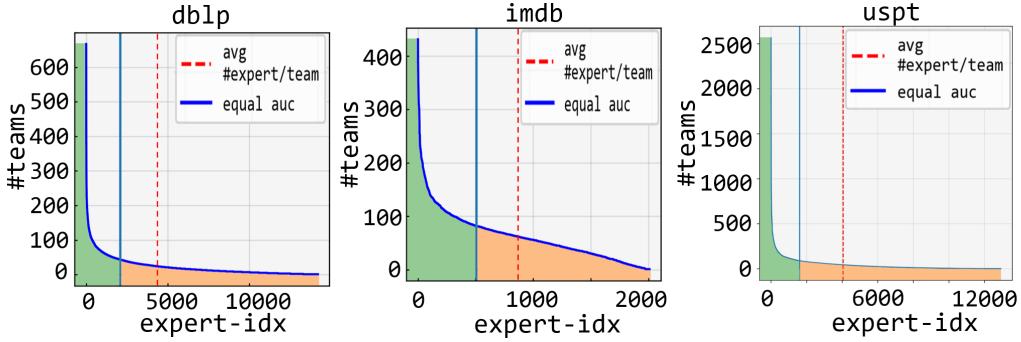


FIGURE 2 Distribution of experts in terms of popularity in dblp, imdb, and uspt datasets. While defining popularity can be controversial, recommender system literature follows *sociometric* popularity⁹⁰, where items (herein, experts) of the *head* in the participation distribution are labeled as popular items. As seen, there are two alternatives to split the distribution into *head* and *tail* parts: *i*) the average number of teams per expert over the entire dataset, or *ii*) equal area under the curve (auc). In this paper, we opt for the former. For the dblp dataset, the average stands at 23.02 teams, 62.45 teams for the imdb dataset, and 44.69 teams for the uspt dataset. Therefore, in dblp, the proportion of popular to nonpopular experts becomes 0.313 to 0.687, in imdb, it is 0.426 to 0.574 and for uspt it stands at 0.314 to 0.686.

- 58 2. We proposed a model-agnostic post-processing and probabilistic reranking method to mitigate unfair biases in the
59 recommended teams of experts by neural team recommendation models.
60 3. We demonstrated the performance of our proposed method in the presence of gender or popularity biases with respect to
61 demographic parity and equality-of opportunity on three large-scale datasets from different domains.
62 4. We developed an open-source reproducible framework hosting canonical neural models as the cutting-edge class of approaches,
63 along with large-scale training datasets from varying domains that integrated our proposed and baseline debiasing reranking
64 algorithms.

65 Our work addresses the ever-growing need to identify and facilitate successful yet diverse teamwork based on merit while
66 fairness is also maximized, which is one of the pillars of growth in scientific and industrial communities. Employers will be
67 able to identify highly-skilled, diverse workers to fill labour gaps and increase innovation. As AI-based solutions are making
68 notable impacts on how job opportunities are allocated to various groups in society, systematic consideration of fairness in this
69 process is key. The rest of the paper is organized as follows: we first present the related works in Section 2, then we continue
70 with the problem definition, where we elaborate basic foundations and formalize fairness objectives based on which a fair team
71 is defined. We propose our approach in Section 3.4. The experimental setup and evaluation are described in Section 4, followed
72 by concluding remarks in Section 5.

73 2 | RELATED WORK

74 The works related to this paper are largely around *i*) neural team recommendation methods and *ii*) fairness-aware recommendation
75 methods.

76 2.1 | Neural Team Recommendation

77 Among the proposed team recommendation methods, we focus on neural models as the cutting-edge computational methods
78 which offer efficiency and effectiveness due to the inherently iterative and online learning procedure. Proposed neural team
79 recommendation models include non-variational feedforward^{24,91}, variational Bayesian network^{62,24,25,91}, and graph neural
80 network^{66,26,33}. Initially, Rad et al.²⁴ defined team recommendation as a multilabel classification task and, as a naive baseline for
81 a minimum level of comparison, developed a simple feedforward network with one hidden layer to map the required subset of
82 skills in the input layer onto a subset of experts in the output layer using the standard cross-entropy loss. Rad et al.^{24,25} then
83 proposed a variational Bayesian network to mitigate the popularity bias through uncertainty in neural model weights in the form

84 of Gaussian distributions. In this line, Dashti et al.²⁷ further proposed negative sampling heuristics assuming groups of experts
 85 who have little or no collaborative experience for the required subset of skills have a low chance for a successful collaboration
 86 and can be considered as *virtually unsuccessful* teams. Given that popular experts were dominant in the training datasets, Dashti
 87 et al. presume that groups of popular experts are more likely to be selected as negative samples of teams. Successfully as they are,
 88 the primary focus of Dashti et al. and Rad et al. was the maximization of the efficacy by tailoring the recommended experts for a
 89 team to the required skills only, overlooking to substantiate whether the higher efficacy comes with mitigation of popularity bias.

90 Sapienza et al.⁶⁶ were the first to use a graph neural network in the form of an autoencoder for team recommendation in online
 91 multiplayer games. Later, Rad et al.²⁶ proposed to transfer dense vector representations of skills for the input of variational
 92 Bayesian neural network from a heterogeneous graph whose nodes are teams, experts, skills, and locations and edges connect
 93 experts who have collaborated in a team residing in a location using Dong et al.'s metapath2vec⁹² and obtained the state-of-
 94 the-art performance. More recently, Kaw et al.³³ employed deep graph infomax⁹³, a graph convolution network with attention
 95 layer as an encoder, to learn more effective vector representations of skills in less training epochs owing to the convolutional
 96 architecture and contrastive learning procedure.

97 Nonetheless and despite a few efforts^{24,25,27}, existing neural team recommendation models still withhold extreme biases.
 98 Meanwhile, accounting for fairness in neural models has gained significant importance for their widespread applications in
 99 everyday lives, like in healthcare^{94,95,96,97}, information retrieval^{98,99}, computer vision^{100,101,102,103,104}, and recommendation
 100 systems^{34,105,106,20,36,21,107,108}. To this end, in this paper, we are among the first to formalize the fair team recommendation
 101 problem with respect to group-based notions of fairness and undertake an empirical investigation to bridge the fairness gap
 102 through a probabilistic post-processing reranking method in favor of recommending more female or nonpopular experts while
 103 controlling the accuracy of the recommended teams.

104 2.2 | Fairness-aware Team Recommendation

105 Theoretically, fairness guarantees in machine learning algorithms have been defined at an individual level⁹ where an individual
 106 should be treated consistently¹⁰ or based on a group of individuals where a disadvantaged group, ~~also known as a protected group~~,
 107 should be treated similarly to the advantaged group as a whole^{8,6}. Different fairness-aware methods have been proposed to either
 108 discover and measure unfair biases¹⁰⁹, or to mitigate them via debiasing algorithms^{34,105,85,36,107,86} at individual or group levels.

109 Debiasing algorithms can further be categorized based on their placement in the machine learning pipeline: *i*) pre-
 110 processing^{76,77,78,19} methods modify data or its labels by re-sampling heuristics before model training, *ii*) in-processing^{79,80,20,21,22}
 111 techniques modify models' optimization process to trade-off accuracy with fairness considerations, and *iii*) post-
 112 processing^{82,83,34,84,85,22,36,86} methods modify models' outputs during inference, which may involve modifying thresholds,
 113 scoring rules, or reranking of the recommended list of items^{110,7}. The latter category is of particular interest ~~for it can be~~
 114 ~~model agnostic and plugged into a model with little to no modification to the model's architecture or negative impact on its~~
 115 ~~predictive power~~, due to several practical advantages. Foremost, post-processing methods are computationally efficient, as they
 116 do not require access to or manipulation of raw training data, which are typically medium- to large-scale, unlike pre-processing
 117 or in-processing methods^{15,16}. Secondly, post-processing methods can be readily plugged into already trained and deployed
 118 models without retraining or fine-tuning, a scenario that is increasingly common in realistic settings where pre-processing or
 119 in-processing interventions are infeasible. Finally, post-processing methods are more privacy-preserving, as they do not require
 120 access to potentially sensitive raw training data, as in pre-processing methods, nor the architecture or parameters of private
 121 models, as in in-processing methods^{17,18}.

122 Related to this paper, we explain seminal reranking debiasing methods that achieve group-based fairness in recommendation
 123 tasks. Geyik et al.³⁶ propose greedy reranking algorithms to ensure prior desired distributions for disadvantaged protected group
 124 within the top- k items. At each iteration i ; $1 \leq i \leq k$, lower and upper bounds are calculated for protected group members
 125 to guarantee the desired distribution within top- i . To measure bias in original rankings and rerankings, they use skew³⁶ and
 126 normalized discounted cumulative KL-divergence (ndkL)¹⁰⁹. Geyik et al.'s algorithms are, however, deterministic and fall short
 127 in the presence of real-world uncertainties. In contrast, Zehlike et al.³⁴ have proposed a probabilistic method to produce a top- k
 128 ranking while maintaining fairness towards multiple protected groups. They rely on statistical tests and aim for a minimum
 129 proportion of protected items in each subset of the ranked items. Utilizing cumulative distribution functions, they calculate the
 130 minimum number of required protected items at a given position to hold the fairness criteria with a pre-defined confidence level.
 131 Instead of providing rigid decisions, they offer distributions over possible outcomes, ensuring that items with small probabilityties
 132 are not completely disregarded.

To the best of our knowledge, there is yet to be a neural team recommendation method that specifically takes fairness into account except Loghmani et al.³⁵, wherein the application of deterministic reranking algorithms³⁶ to mitigate popularity bias in neural team recommenders^{25,24,27} were shown futile due to the substantial compromise to the models' accuracy. Building upon Zehlike et al.³⁴'s work, we adapt a probabilistic reranking method for the team recommendation task. However, unlike item-level ranking in their work, team recommendation requires rankings of experts for a team compositions while enforcing fairness over the team as a whole. Our method incorporates team-level success probabilities instead, which is absent in Zehlike et al.

3 | FAIR NEURAL TEAM RECOMMENDATION

In this section, we introduce the necessary notations and definitions for neural team recommendation, on the one hand, and group-based fairness, on the other hand. Then, we provide a formal problem statement to recommend a fair team of experts.

3.1 | Preliminaries

Given a set of skills $\mathcal{S} = \{s\}$ and a set of experts $\mathcal{E} = \{e\}$, a team of experts $E \subseteq \mathcal{E}; E \neq \emptyset$ that collectively cover a skill set $S \subseteq \mathcal{S}; S \neq \emptyset$ is shown by (S, E) along with its success status y where $y \in \{0, 1\}$ which is known *a priori*. Further, $\mathcal{T} = \{(S, E)_y : y \in \{0, 1\}\}$ indexes all teams, successful and unsuccessful. In team recommendation literature^{66,111,50,112,113,114,115,116}, an expert's set of skills has been *estimated* through her participation in successful teams denoted by $S_e = \{s : (s \in S, e \in E)_{y=1} \in \mathcal{T}\}$, i.e., an expert member of a successful team inherits *all* the required skills of the team, as the expert obtains knowledge about all required skills through collaboration with other expert members of the team.

Definition 1 (Team Recommendation). For a given subset of required skills S , the goal of the team recommendation problem is to recommend an optimal subset of experts E whose collaboration as a team leads to success, i.e., $(S, E)_{y=1}$, while avoiding a potentially unsuccessful subset of experts E' , i.e., $(S, E')_{y=0}$. More concretely, the team recommendation problem is to find a mapping function f of parameters θ from the power set of skills to the powerset of experts such that $f_\theta : \mathcal{P}(\mathcal{S}) \rightarrow \mathcal{P}(\mathcal{E}), f_\theta(S) = E$.

As shown in Figure 2, the output of a neural team recommendation method for a required set of skills S is a ranked list of all experts where each expert $e \in \mathcal{E}$ is assigned a probability of her membership in the final recommended team. The recommended team is a subset of experts $E \subseteq \mathcal{E}$ with the top k highest probabilities.

Definition 2 (Neural Team Recommendation). Given a subset of skills S and all teams \mathcal{T} as the training set, neural team recommendation estimates $f_\theta(S)$ using a multilayer neural network that learns, from \mathcal{T} , to map a vector representation of subset of skills S , referred to as v_S , to a vector representation of subset of experts E , referred to as v_E , by maximizing the posterior probability of θ in f_θ over \mathcal{T} , that is, $\text{argmax}_\theta p(\theta|\mathcal{T})$.

For the vector representation of subset of skills v_S , neural team recommendation methods adopt either

1. The *occurrence* vector representation for S , which is a Boolean vector of size $|S|$, i.e., $v_S \in \{0, 1\}^{|S|}$ where $v_S[s] = 1$ if $s \in S$, and 0 otherwise, or
2. The *embedding* representation of S , which is a dense low d -dimensional vector, $d << |S|$, pretrained by e.g., a shallow neural encoder²⁵ like in distributional representation of words (word2vec)³¹ and documents (doc2vec)³², or a graph neural network method^{33,26}.

While occurrence vector representations are simple, they lead to high-dimensional sparse input representations, substantially increasing the number of trainable parameters in the input layer of neural networks. In contrast, dense pretrained vectors (embeddings) provide low-dimensional, continuous representations that significantly reduce model complexity and enable more stable and data-efficient learning. Moreover, dense embeddings capture latent semantic relationships among skills, allowing the model to generalize across similar inputs rather than treating each skill as independent, as is the case with the occurrence representation.

In the output layer for vector representation of subset of experts v_E , neural team recommendation methods frame the problem as a multilabel Boolean classification task and used occurrence vector representation for E , that is, $v_E \in [0, 1]^{|E|}$ where $v_E[e] = 1$ if $e \in E$, and 0 otherwise. Using a neural model of one hidden layer \mathbf{h} of size d , without loss of generality to multiple hidden

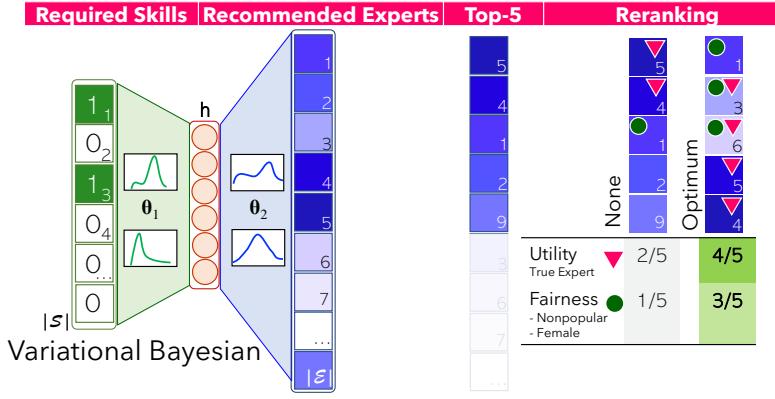


FIGURE 3 Post-processing fairness-aware reranking for fair neural team recommendation. ∇ indicates the correctly predicted expert (accuracy) and \bullet shows members of the protected group (fairness). The goal is to maximize fairness while maintaining the model’s accuracy.

layers, with the input layer v_S and output layer v_E , a neural team recommendation method can be formalized as^{91,27,63,26,24}:

$$\mathbf{h} = \pi(\boldsymbol{\theta}_1 v_S + \mathbf{b}_1) \quad (3)$$

$$\text{logits} \rightarrow \mathbf{z} = \boldsymbol{\theta}_2 \mathbf{h} + \mathbf{b}_2 \quad (4)$$

$$v_E = \sigma(\mathbf{z}) \quad (5)$$

where π is a nonlinear activation function, σ is the sigmoid function, and $\boldsymbol{\theta} = \boldsymbol{\theta}_1 \cup \boldsymbol{\theta}_2 \cup \mathbf{b}_1 \cup \mathbf{b}_2$ are learnable parameters for the mapping function f . During training, given a team (S, E) , neural models tune the parameters $\boldsymbol{\theta}$ by maximizing the posterior probability of $\boldsymbol{\theta}$ in $f_{\boldsymbol{\theta}}$ over \mathcal{T} . From Bayes theorem:

$$\text{argmax}_{\boldsymbol{\theta}} p(\boldsymbol{\theta} | \mathcal{T}) \propto p(\mathcal{T} | \boldsymbol{\theta}) p(\boldsymbol{\theta}) = p(\boldsymbol{\theta}) \prod_{(S, E)_{y=1} \in \mathcal{T}} p(E | S, \boldsymbol{\theta}) \quad (6)$$

$$p(E | S, \boldsymbol{\theta}) = \prod_{j \in e} \sigma(z[j]) \propto \sum_{j \in e} \log \sigma(z[j]) \quad (7)$$

where $p(\mathcal{T} | \boldsymbol{\theta})$ is the likelihood and $p(\boldsymbol{\theta})$ is the prior joint probability of weights, which is unknown. While the exact prior probability of weights $p(\boldsymbol{\theta})$ cannot be calculated analytically²³, it can be estimated as Gaussian distributions by a variational Bayesian neural architecture via the maximum a posteriori optimization^{24,25,26}, which contrasts with conventional *non*-variational multilayer perceptron that assume a *uniform* probability distribution over all possible real-values of $\boldsymbol{\theta}$ and only estimate the likelihood $p(\mathcal{T} | \boldsymbol{\theta})$ via maximum likelihood optimization, discarding prior uncertainty $p(\boldsymbol{\theta})$, and hence, resulting in overconfident point estimates of $\boldsymbol{\theta}$ ²³. Existing studies primarily adopt standard multilayer perceptrons (non-variational feedforward neural networks) as baselines to demonstrate the performance advantages of variational neural networks^{27,28,23}.

As shown in Figure 3, the output of a neural team recommendation method for a required set of skills S is a ranked list of *all* experts where each expert $e \in \mathcal{E}$ is assigned a probability of her membership in the final recommended team. The recommended team is a subset of experts $E \subseteq \mathcal{E}$ with the top- k highest probabilities to form a team size of k members.

3.2 | Successful Teams

From Definition 1 and 2, neural team recommenders aim at estimating f from samples of teams that are labeled with success or failure, yet most available training data in team recommendation literature only consists of successful teams, missing *un*successful ones. For instance, the dblp lacks unsuccessful paper or manuscript submissions. Further, what it means for a team to be successful has remained controversial. For instance, in the movie industry, it is debatable whether a movie’s success should be measured based on its immediate reception by the people (box office) or critical reviews (ratings) over a long span of time. In the absence of explicit labels for unsuccessful teams, neural team recommendation methods presume all instances of teams in the

189 training dataset are successful (positive samples) for their observable outcomes, e.g., *published* papers in dblp, *issued* patents
 190 in uspt, and *produced* movies in imdb, that is, $\mathcal{T} = \mathcal{T}^+ = \{(S, E)_{y=1}\}$ and proceed with the training procedure^{26,24,25,33}.
 191 As a result, during the inference, for an input required set of skill S, the models predict (recommend) a subset of experts E
 192 for a successful team only, i.e., $(S, E)_{y=1}$ and the learned probabilities in Equations 5 and 6 should be interpreted as expert's
 193 membership likelihood for a successful team. Throughout the remainder of this paper, we therefore assume $y = 1$ whenever a
 194 team $(S, E)_y$ is considered, and the act of recommending a team is understood as recommending a potentially successful team, as
 195 recommending *unsuccessful* teams $(S, E)_{y=0}$ is not desired.

196 3.3 | Fair Team Recommendation

197 To eschew varied interpretations and to provide actionable criteria to design and evaluate fairness-aware algorithms, fairness
 198 has been mathematically formalized, with a level of abstraction from an underlying real-world scenario, based on well-known
 199 notions of justice and equity at an individual level^{9,10}, or at a group level^{1,7,8,6} like female vs. male experts. In this paper, we
 200 focus on group-based notions of fairness.

201 3.3.1 | Protected Attribute and Group

202 We define a (social) group \mathcal{G} as a subset of the experts \mathcal{E} that shares an “*identity trait*”¹, which may be inherent to an expert and
 203 largely immutable, that is, cannot reasonably be expected to change through choice, effort, or behavior, and is considered sensitive
 204 due to its historical association with systemic discrimination, e.g., gender. As a result, legal frameworks and policies have been
 205 developed to protect the group members, e.g., female experts, from differential treatment based on the group's shared identity
 206 trait and to promote fairness, equal opportunity, and anti-discrimination across institutional and algorithmic decision-making
 207 processes¹¹⁷. Hence, the shared identity trait based on which the groups are formed is referred to as the *protected attribute* \mathcal{A}
 208 whose values create $|\mathcal{A}|$ *protected groups* such that experts of a protected group share the same value for the protected attribute.

209 **Gender as a Canonical Protected Attribute:** In this paper, given the protected attribute $\mathcal{A}:\text{gender}$, the values= $\{a : \text{female}, a' : \text{male}\}$
 210 create *disjoint* protected groups of experts including female experts $\mathcal{G}_{a:\text{female}}$ and male experts $\mathcal{G}_{a':\text{male}}$ where $\mathcal{E} =$
 211 $\mathcal{G}_{a:\text{female}} \cup \mathcal{G}_{a':\text{male}}$ while $\mathcal{G}_{a:\text{female}} \cap \mathcal{G}_{a':\text{male}} = \emptyset$. To form the gender groups, we presume an expert's gender value is self-
 212 identified and is either available, e.g., in uspt dataset of US patent inventors, or can be inferred by the expert role, e.g., actor
 213 vs. actress in imdb dataset of movies, or the expert's name in dblp dataset of scholarly papers. It is worth noting that, when
 214 gender values are inferred rather than directly observed, they may inherently incorporate societal biases, or even amplify pre-
 215 existing stereotypes in society^{29,30}, as further illustrated by examples in our experimental setup (Section ??). Therefore, fairness
 216 assessments and bias mitigation using these inferred values may over- or under-estimate disparities across groups, and results
 217 should be interpreted with this limitation in mind. As seen earlier in Figure 1, experts in team recommendation datasets are
 218 disproportionately distributed toward male experts. Therefore, we consider the *minority* female group as the disadvantaged
 219 group vs. the *majority* male group as the advantaged group.

220 **Popularity as an Unconventional Protected Attribute:** As highlighted by Gallegos et al. and others^{1,2}, a group can also be
 221 formed based on an identity trait that is contextual, e.g., disability, dynamic, e.g., religion, or socially constructed based on
 222 social network effects and historical contingencies, like outcomes or conditions that arise from past events, as in popularity^{3,4,5}.
 223 However, treating popularity as a protected attribute receives limited or no attention within legal frameworks and policies, as
 224 it is weakly aligned with the characteristics of commonly known protected attributes like gender, especially in the context of
 225 the team recommendation problem. (1) Foremost, protected attributes are typically defined to protect a *minority* group from
 226 being marginalized by a *majority* group, e.g., to ensure that female experts are not under-represented in team recommendations
 227 relative to male experts. In contrast, when considering popularity, the aim is reverse, that is, to protect the majority nonpopular
 228 experts from the minority popular experts who disproportionately dominate team participation. (2) Secondly, popularity can
 229 act as a proxy, a justified signal of merit, or a shortcut for expertise, experience, and success. Highly skilled experts tend to
 230 be repeatedly successful, and hence selected for more teams, which increases both their participation count and visibility, and
 231 eventually results in their being popular. Respectively, popularity correlates with perceived expertise^{118,119}, and favoring popular
 232 experts appears rational and performance-driven, rather than unfair^{120,121}. (3) Finally, popularity can also be interpreted as being

widely liked, acclaimed, or recognized by others, often associated with reputation or fame, reducing of which may itself be unfair to popular experts.

On the other hand, popularity can induce systematic undesirable outcomes, should it otherwise be treated as a protected attribute. Although an expert’s participation in many teams, e.g., an author in many research papers in dblp or an actor in many movies in imdb, may *not* necessarily indicate popularity from the people’s *subjective* perspectives, repetition of the expert in many training samples of teams from a machine learning model’s perspective does. In particular,

- From societal perspective, when experts’ popularity is used naively, either directly as a feature, that is, being popular or not, or indirectly through an imbalance pool of expert candidates with long-tailed distribution of few minority but dominant experts (popular) in the head against majority experts (non-popular) in the tail, team recommendation processes leads to, or amplify, persistent under-representation of less- or nonpopular experts, who may possess comparable expertise but lack historical opportunities to accumulate participation records but ultimately receive reduced access to opportunities such as team membership. Moreover, popularity is influenced by factors orthogonal to expertise. Two experts with comparable skills may diverge in popularity due to institutional affiliation¹²⁰, geographic factors^{122,123}, or historical chances^{118,124}. In such cases, consistently preferring the popular expert represents unjustified, unfair, and disproportionate exclusion, not merit-based selection, of nonpopular experts.
- From an algorithmic perspective, as extensively studied in team science^{125,126,127}, teams composed solely of popular experts are not necessarily optimal in terms of cost or availability of experts, or even successful due to the “*too-much-talent effect*”¹²⁸; rather complementary skills with heterogeneous levels of expertise provided by nonpopular experts are required. Canonical examples include research teams consisting of senior supervisors and junior students, or industrial teams balancing experts with trainees. Also, many contributions have come from nonpopular experts despite their lower visibility¹²⁹. Moreover, practical constraints such as availability, cost, or workload often make popular experts infeasible choices, further undermining the assumption that popularity-driven recommendations are universally applicable^{130,131,132}.
- Popularity as a biased feature, as opposed to a protected attribute, is the largely shared understanding and has been well-studied in recommender systems in the context of item recommendation^{133,134,135}, where popularity is defined over items as a statistical bias arising from long-tailed (skewed) user-item interaction distributions. Yet, interestingly, or rather counterintuitively, few item recommender systems explicitly treat item popularity as a protected attribute^{3,4} or a sensitive attribute⁵. They either partition items into popular (head) and nonpopular (tail) groups and adjust the learning process to protect the nonpopular items in the tail group, or explicitly model the effect of item popularity as a sensitive feature and remove its influence on rankings.
- Treating popularity as a protected attribute enables mitigation strategies in a unified and technically coherent algorithmic framework in which attributes, whether legally protected or socially constructed, are handled consistently, reducing implementation complexity and improving comparability across models.

Therefore, in social information retrieval systems, including team recommender systems, expert recommender systems, or social talent search engines^{136,36,137}, where the entities being recommended are *human* experts rather than items, we argue that the popularity should be treated as a protected attribute, with particular emphasis on protecting nonpopular experts as less-exposed disadvantaged group, to prevent unfair societal implications like systematic reduced access to team memberships^{121,138}. Accordingly, in this paper, given the protected attribute \mathcal{A} :popularity, the values= $\{a : \text{nonpopular}, a' : \text{popular}\}$ create disjoint protected groups of experts including nonpopular experts $\mathcal{G}_{a:\text{nonpopular}}$ and popular experts $\mathcal{G}_{a':\text{popular}}$ where $\mathcal{E} = \mathcal{G}_{a:\text{nonpopular}} \cup \mathcal{G}_{a':\text{popular}}$ while $\mathcal{G}_{a:\text{nonpopular}} \cap \mathcal{G}_{a':\text{popular}} = \emptyset$. We consider the *majority* nonpopular group as the disadvantaged group vs. the *minority* popular group as the advantaged group.

To obtain an expert’s popularity status, we followed social science⁹⁰ and recommender system literatures^{139,140}, where the popularity status of an expert can be *objectively* measured based on the number of teams the expert has participated in, referred to as *sociometric popularity*⁹⁰. We can adopt two alternatives, as shown in Figure 2: *i*) an expert is popular if the expert participated in more than the average number of teams per expert over the entire dataset, and nonpopular otherwise (avg), or *ii*) we plot the distribution of experts in teams and split the curve into *short head* and *long tail* based on equal area under the curve (auc) should it be long-tail distribution. An expert is popular if she belongs to the short head, and nonpopular otherwise. As seen earlier in Figure 2, experts in team recommendation datasets are disproportionately distributed toward popular experts.

Given a protected attribute $a = \{a_1, \dots, a_n\}$, e.g., gender= $\{0: \text{male}, 1: \text{female}\}$ or popularity= $\{0: \text{popular}, 1: \text{nonpopular}\}$, we divide experts into groups per their attribute values, each referred to as a protected group \mathcal{G}_a , e.g., female \mathcal{G}_1 vs. male \mathcal{G}_0 experts, or nonpopular \mathcal{G}_1 vs. popular \mathcal{G}_0 experts, such that experts of a protected group share the same value for a protected attribute.

283 We now define the notions of group fairness for team recommendation as follows.

284 **3.3.2 | Demographic Parity**

285 Demographic parity, also called statistical parity⁶, is to provide equal treatment to protected groups, i.e., the proportion of
286 individuals receiving a favorable outcome should be consistent across all protected groups regardless of protected attributes.

287 Given \mathcal{D} the set of possible decisions, demographic parity requires the *predicted* decision $\hat{d} \in \mathcal{D}$ for members of protected
288 groups to be oblivious to the protected attribute^{6,1,11,12}. Formally,

$$\cancel{\forall d \in \mathcal{D}, i \neq j \in \mathcal{A}; p(\hat{d} | e_{a_i}) = p(\hat{d} | e'_{a_j})} \quad (8)$$

$$\forall \hat{d} \in \mathcal{D} \forall a \in \mathcal{A}: p(\hat{d} | e \in \mathcal{G}_a) = p(\hat{d}) \quad (9)$$

289 where \hat{d} is the predicted decision for the ~~correct~~ground-truth decision d , and ~~$e_{a_i} \in \mathcal{G}_{a_i}$ is an expert whose value of protected~~
290 ~~attribute a is a_i , $e \in \mathcal{G}_a$ are experts in a disjoint group \mathcal{G}_a whose values of the protected attribute \mathcal{A} are a .~~ It is worth noting
291 that demographic parity is also independent of the ground-truth decision, that is, whether the predicted decision is correct or
292 otherwise.

In fair team recommendation, we assume decisions \mathcal{D} are about the Boolean membership status of experts in ~~the team of~~
~~experts E , i.e., $e \in E$ or $e \notin E$~~ a successful team $(S, E)_{y=1}$, i.e., $\hat{d} \in \mathcal{D} = \{e \in E, e \notin E\}$, and protected attributes \mathcal{A} are either
gender or popularity. Hence, Equation 9 becomes:

$$\cancel{\forall e_0, e'_1 \in \mathcal{E}; [p(e_0 \in E) = p(e'_1 \in E)] \wedge [p(e_0 \notin E) = p(e'_1 \notin E)]} \quad (10)$$

$$\forall a \in \mathcal{A}: [p(e \in E | e \in \mathcal{G}_a) = p(e \in E)] \wedge [p(e \notin E | e \in \mathcal{G}_a) = p(e \notin E)] \quad (11)$$

Proposition 1. *Demographic parity for fair team recommendation holds if and only if*

$$\forall a \in \mathcal{A}: p(e \in E | e \in \mathcal{G}_a) = p(e \in E) \quad (12)$$

294 *Proof.* Since $p(e \in E | e \in \mathcal{G}_a) + p(e \notin E | e \in \mathcal{G}_a) = 1$, it follows that $p(e \in E | e \in \mathcal{G}_a) = 1 - p(e \notin E | e \in \mathcal{G}_a)$. Therefore,
295 Equation 12 directly implies $p(e \notin E | e \in \mathcal{G}_a) = p(e \notin E)$. \square

296 Intuitively, demographic parity requires that the likelihood of being recommended for a successful team is independent of the
297 values of any protected attribute, such as popularity, gender, or ethnicity. In other words, belonging to a particular protected
298 group should neither increase nor decrease an expert's chance of being part of a successful team.

299 In this paper, we focus on recommended teams within a post-processing reranking framework. To ensure fairness, we need to
300 check, measure, and, if necessary, debias recommended teams after they have been predicted by a neural team recommendation
301 model described in Section 3.1. In the following proposition, we show that demographic parity is satisfied if and only if the
302 *posterior* distribution of experts from each protected group in the recommended team matches their *prior* distribution in the
303 overall pool of experts \mathcal{E} . This result is particularly useful for post-hoc assessment and reranking. After recommending a team $(S, E)_{y=1}$,
304 we can examine the posterior probabilities of experts from each protected group and, if necessary, adjust team membership
305 to satisfy fairness constraints.

306 **Proposition 2.** *Demographic parity holds in the fair team recommendation problem if and only if the posterior distributions
307 of experts of protected groups in the successful team is equal to their prior distribution in the entire set of experts \mathcal{E} , i.e.,
308 $p(e \in \mathcal{G}_a | e \in E) = p(e \in \mathcal{G}_a)$.*

Proof. By Bayes theorem,

$$p(e \in \mathcal{G}_a | e \in E) = \frac{p(e \in E | e \in \mathcal{G}_a) p(e \in \mathcal{G}_a)}{p(e \in E)} \stackrel{\text{Equation 12}}{=} p(e \in \mathcal{G}_a | e \in E) = p(e \in \mathcal{G}_a) \quad (13)$$

309

□

310 **Example 1.** Consider a set of $|\mathcal{E}| = 100$ experts, where \mathcal{A} denotes gender, and $|\mathcal{G}_{a:\text{female}}| = 30$ and $|\mathcal{G}_{a':\text{male}}| = 70$ represent the
 311 groups of female and male experts, respectively. Suppose we want to recommend a team of size $k = 10$ for a required set of
 312 skills S , i.e., $(S, E)_{y=1}$. To satisfy demographic parity, each expert's probability of being selected can be assumed independent
 313 and identically distributed (i.i.d.), with uniform probability across all experts, which gives $\frac{k}{|\mathcal{E}|} = \frac{10}{100} = 0.10$ from Equation 12,
 314 regardless of the expert's gender. That is, every female and male expert has an equal chance of being selected. Conversely, from
 315 Proposition 2, demographic parity also requires that the composition of the recommended team reflects the overall population.
 316 Specifically, the prior distribution of female and male experts, $p(e \in \mathcal{G}_{a:\text{female}}) = \frac{|\mathcal{G}_a|}{|\mathcal{E}|} = \frac{30}{100} = 0.3$ and $p(e \in \mathcal{G}_{a':\text{male}}) = \frac{|\mathcal{G}_{a'}|}{|\mathcal{E}|} =$
 317 $\frac{70}{100} = 0.7$, should match their posterior distribution in the recommended team E with $p(e \in \mathcal{G}_a \mid e \in E) = \frac{3}{10} = 0.3$ and
 318 $p(e \in \mathcal{G}_{a'} \mid e \in E) = \frac{7}{10} = 0.7$. In this way, the recommended team satisfies demographic parity.

319 ~~Intuitively, demographic parity enforces the membership in a team to be independent of values of a protected attribute for
 320 team members, i.e., no regard to their popularity, gender, ethnicity, or any other protected characteristic. However, demographic
 321 parity overlooks experts' qualifications; no criteria for experts' memberships has been defined in Equation 12 and Equation 13.~~

322 However, demographic parity alone overlooks the qualifications of experts; no criteria for membership have been defined in
 323 Equations 9, 11, 12, and 13. In Example 1, giving all experts an equal chance of selection without considering their expertise with
 324 respect to the required set of skills S would substantially reduce the quality of the recommended team E for a successful team $(S, E)_{y=1}$. Indeed, Example 1 represents a worst-case scenario based on a random selection model; while it satisfies demographic
 325 parity, the team is essentially a uniformly random set of experts, which may not perform effectively. Therefore, ensuring fairness
 326 alone is not sufficient and expert qualifications must also be incorporated to maintain team quality while satisfying fairness, as
 327 captured by equalized odds and equal opportunity, discussed below.

329 3.3.3 | Equalized Odds

Equalized odds^{7,13} is a stronger notion of fairness. While demographic parity emphasizes equal treatment by ensuring a similar proportion of positive outcomes across protected groups, equalized odds go further by ensuring that the ranking is equitable across groups for both qualified and non-qualified cases. In other words, it applies demographic parity on subsets of protected groups whose members are qualified (not qualified) for the ground-truth decision d to receive the ~~correct predicted~~ decision \hat{d} in a ~~Boolean decision set and Boolean protected attribute~~. Formally,

330

$$\forall d \in \mathcal{D} = \{0, 1\}; p(\hat{d} \mid e_0, d) = p(\hat{d} \mid e_1, d) \quad (14)$$

$$\forall d, \hat{d} \in \mathcal{D} \forall a \in \mathcal{A}: p(\hat{d} \mid e \in \mathcal{G}_a, d) = p(\hat{d} \mid d) \quad (15)$$

331 Unlike demographic parity (Equation 9), equalized odds allows the predicted decision \hat{d} to depend on the ground-truth decision
 332 d . As such, for the fair team recommendation with the Boolean decision set, it allows the use of the required subset of skills S
 333 that predicts ground-truth decision $d \in \mathcal{D} = \{e \in E, e \notin E\}$ in $(S, E)_{y=1}$ for experts who have the skills S versus other experts.

334 Given an expert e along with her set of skills S_e (Section 3.1), the expert is *qualified* for a team with a required subset of
 335 skills S if the expert's skill set has a nonempty intersection with S , that is, $S_e \cap S \neq \emptyset$ [†]. From Equation 15 and mapping the
 336 ground-truth decisions to the experts' qualifications as $d \in \mathcal{D} = \{(e \in E \iff S_e \cap S \neq \emptyset), (e \notin E \iff S_e \cap S = \emptyset)\}$, that
 337 is, being in the recommended team depends on the overlap between the experts' skills S_e and the required set of skill S , we have:

$$\forall \hat{d} \in \mathcal{D} \forall a \in \mathcal{A}: p(\hat{d} \mid e \in \mathcal{G}_a, S_e \cap S) = p(\hat{d} \mid S_e \cap S) \quad (16)$$

Equivalently,

$$\forall a \in \mathcal{A}: [p(e \in E \mid e \in \mathcal{G}_a, S_e \cap S) = p(e \in E \mid S_e \cap S)] \wedge [p(e \notin E \mid e \in \mathcal{G}_a, S_e \cap S) = p(e \notin E \mid S_e \cap S)] \quad (17)$$

[†] Alternatively, as future work, we can define other qualification measures, e.g., the size of the intersection, to show more (less) qualified experts.

and similar to proposition 1, equalized odds for fair team recommendation holds if and only if,

$$\forall a \in \mathcal{A} : p(e \in E | e \in \mathcal{G}_a, S_e \cap S) = p(e \in E | S_e \cap S) \quad (18)$$

As seen, equalized odds ensure demographic parity given the qualifications of experts for the input required set of skills S for the recommended successful team $(S, E)_{y=1}$. In other words, the likelihood of being in the recommended team only depends on whether an expert is qualified, regardless of the expert's value of the protected attribute.

Example 2. From Example 1, for a set of $|\mathcal{E}| = 100$ experts, where \mathcal{A} denotes gender, $|\mathcal{G}_{a:\text{female}}| = 30$ and $|\mathcal{G}_{a':\text{male}}| = 70$ represent female and male groups, respectively. To recommend a fair team of size $k = 10$ for a required set of skills S , we first identify the qualified and unqualified experts. Suppose there are 10 female and 10 male experts whose skill sets intersect with S (i.e., qualified experts), and the remaining 20 female and 60 male experts are not qualified. To satisfy equalized odds, an expert's probability of being selected can be assumed to be independent and identically distributed (i.i.d.) and uniform *within each qualification group*. Specifically, (1) the probability that a qualified expert is selected into the team is $\frac{k}{10+10} = \frac{10}{20} = 0.5$, as given by Equation 18, regardless of gender. Thus, every qualified female and male expert has an equal chance of being selected. (2) Equally importantly, the probability that an unqualified expert is selected into the team is $\frac{k}{20+60} = \frac{10}{80} = 0.125$, again regardless of gender. Hence, all unqualified female and male experts also have equal selection probability. Now consider an imperfect base recommender model whose top- $k=10$ recommendations include 6 qualified experts and 4 unqualified experts. To satisfy equalized odds, the qualified subset should be distributed as $0.5 = \frac{x}{6}$, yielding $x = 3$ female and $6 - x = 3$ male experts. The remaining unqualified experts should be distributed by $0.125 = \frac{x}{4}$, resulting in $[0.5] = 1$ unqualified female experts and $4 - 1 = 3$ male experts.

In fair team recommendation, equalized odds would ensure that among skilled experts, individuals from different protected groups have equal chances of appearing in top positions, while among unqualified members, the likelihood of being incorrectly ranked highly remains consistent across protected groups. In other words it guarantees that the protected groups have equal true positive rates and false positive rates simultaneously. A *qualified* expert e for a team with a required subset of skills S can be simply defined as a Boolean measure based on whether the expert's skill set has a nonempty intersection with S , that is, $S_e \cap S \neq \emptyset$. Alternatively, as future work, we can consider a non-Boolean measure, such as the size of the intersection, to identify more (or less) qualified experts.

3.3.4 | Equality-of Opportunity

Equality-of opportunity is a relaxed version of equalized odds that only requires fairness for the desired ground-truth decision, that is, the '*opportunity*' among *qualified* experts⁷. The intuition is to ensure that among *individuals* experts who are qualified for a positive outcome, the probability of receiving a positive prediction should be equal regardless of their protected attributes. This is less restrictive than equalized odds but can be more practical to implement while still preventing discrimination against qualified *individuals* experts from protected groups.

For a fair team recommendation with a Boolean decision $d \in \mathcal{D} = \{(e \in E \iff S_e \cap S \neq \emptyset), (e \notin E \iff S_e \cap S = \emptyset)\}$, if we prioritize fairness for the qualified experts, i.e., $d = (e \in E \iff S_e \cap S \neq \emptyset)$ to be '*recommended*' in a team as an advantaged outcome, i.e., $\hat{d} = e \in E$, and ignore the possible discrimination for the *unqualified* experts caused by the same decision, i.e., $\hat{d} = e \in E$ but $S_e \cap S = \emptyset$, we have a less strict variant of equalized odds from Equation 18, as follows:

$$\forall a \in \mathcal{A} : p(e \in E | e \in \mathcal{G}_a, S_e \cap S \neq \emptyset) = p(e \in E | S_e \cap S \neq \emptyset) \quad (19)$$

Proposition 3. Equal opportunity holds in the fair team recommendation problem if and only if the posterior distributions of experts of protected groups in the successful team is equal to their prior distribution in the entire set of '*qualified*' experts \mathcal{E} , i.e., $p(e \in \mathcal{G}_a | e \in E, S_e \cap S \neq \emptyset) = p(e \in \mathcal{G}_a | S_e \cap S \neq \emptyset)$.

Proof. By Bayes theorem,

$$\begin{aligned} p(e \in \mathcal{G}_a | e \in E, S_e \cap S \neq \emptyset) &= \frac{p(e \in E | e \in \mathcal{G}_a, S_e \cap S \neq \emptyset) p(e \in \mathcal{G}_a, S_e \cap S \neq \emptyset)}{p(e \in E, S_e \cap S \neq \emptyset)} \\ &\stackrel{\text{Equation 19}}{=} p(e \in \mathcal{G}_a | e \in E, S_e \cap S \neq \emptyset) = p(e \in \mathcal{G}_a, S_e \cap S \neq \emptyset) \end{aligned} \quad (20)$$

370

Example 3. Referring to our earlier Example 2 with a set of $|\mathcal{E}| = 100$ experts, where \mathcal{A} denotes gender, and $|\mathcal{G}_{a:female}| = 30$ and $|\mathcal{G}_{a':male}| = 70$ represent female and male groups, respectively, we aim to recommend a fair team of size $k = 10$ for a required set of skills S . To satisfy equal opportunity, we consider only qualified experts, i.e., 10 female and 10 male experts whose skill sets intersect with S . Assuming independent and identically distributed (i.i.d.) selection with a uniform distribution among qualified experts, each qualified expert is selected with probability $\frac{k}{10+10} = \frac{10}{20} = 0.50$, as given by Equation 19, regardless of gender. Thus, every qualified female and male expert has an equal chance of being selected, while *unqualified experts are excluded from consideration*. Now, given the imperfect base recommender model whose top- $k=10$ recommendations include 6 qualified experts and 4 unqualified experts, to satisfy equal opportunity, from Proposition 3, the qualified subset should be distributed as $0.5 = \frac{x}{6}$, yielding $x = 3$ female and $6 - x = 3$ male experts, as in equalized odds. However, unlike equalized odds, the remaining unqualified experts can be distributed arbitrarily without violating equal opportunity.

If we prioritize fairness for the decision $d = 1$, that is, recommending an expert to be in a team as an advantaged outcome, and ignore the possible discrimination caused by the ‘not recommended’ decision $d = 0$, we have a less strict variant of equalized odds, referred to as equality of opportunity, as follows::

$$\overline{p(\hat{d} | e_0, d = 1)} = \overline{p(\hat{d} | e_1, d = 1)} \quad (21)$$

Hence, from Equation 21 and Equation 22

$$\overline{p(e_0 \in E | e_0, (S_{e_0} \cap S \neq \emptyset))} = \overline{p(e_1 \in E | e_1, (S_{e_1} \cap S \neq \emptyset))} \quad (22)$$

381

It is worth noting that, based on demographic parity, an expert having no required skills might be recommended under demographic parity (Section 3.3.2), recommending an unqualified expert who possesses none of the required skills with the same probability as a qualified expert is still considered fair. In contrast, based on the equalized odds and equal opportunity, members must be qualified for the required skills, that is, the intersection of their skills and the required skills must be non-empty (Equation 18 and Equation 19).

3.3.5 | A Fair Team

Once we define the notions of fairness for the team recommendation problem, we can formalize a fair team by the fair *identity* function \mathbb{I} as follows:

$$\mathbb{I}(E) = \begin{cases} \text{Demographic Parity} & \begin{cases} 1 & \text{iff Equation } \leftrightarrow \text{ Proposition 13} \\ 0 & \text{not a fair team} \end{cases} \\ \text{Equality of Opportunity} & \begin{cases} 1 & \text{iff Equation } \leftrightarrow \text{ Proposition 3} \\ 0 & \text{not a fair team} \end{cases} \end{cases} \quad (23)$$

where E is a subset of experts in a recommended successful team $(S, E)_{y=1}$, which is fair with respect to demographic parity iff Proposition 2. Alternatively, it is fair with respect to the notion of equality of opportunity iff Proposition 3. While equalized odds is a more comprehensive notion of fairness by enforcing parity not only among qualified experts, as in equal opportunity, but also among unqualified experts for the favorable decision of being in a recommended successful team, we do not adopt it in this work. In the context of team recommendation, enforcing parity over unqualified experts is redundant and misaligned with the recommendation objective, wherein models are explicitly trained to identify qualified experts from the required skill set S , and unqualified experts are penalized by the learning objective, as discussed in Section 3.1 and Definition 2. Consequently, outcomes involving unqualified experts are already controlled downstream by the model during training. This observation has also been studied in other predictive models^{37,38,39,40}, leading to the adoption of equal opportunity as a more focused and actionable fairness notion.

TABLE 1 Expert pool of 6 experts showing gender, prior distribution of groups, skills, qualification for the required skill set $S = \{s_1, s_2\}$, and the prior distribution of groups for qualified experts.

\mathcal{E}	$\mathcal{A}=\text{gender}$	$p(e \in \mathcal{G}_a)$	S_e	$S_e \cap S \neq \emptyset$	$p(e \in \mathcal{G}_a S_e \cap S \neq \emptyset)$
e_1	female	$\frac{2}{6} = 0.33$	s_1	✓	$\frac{2}{4} = 0.50$
e_2			s_2	✓	
e_3			s_1	✓	$\frac{2}{4} = 0.50$
e_4	male	$\frac{4}{6} = 0.67$	s_2	✓	
e_5			-	✗	-
e_6			-	✗	-

TABLE 2 Candidate recommended teams E for top- $k=3$ for an *unseen* successful team ($S = \{s_1, s_2\}$, $E_{y=1}$) showing the accuracy of the recommended team based on ground-truth team $E^* = \{\boxed{e_1}, e_3, e_4\}$ who has been indeed successful, posterior group ratios and whether demographic parity and equal opportunity are satisfied based on prior ratios in Table 1.

#	E	$ E \cap E^* $	$p(e \in \mathcal{G}_{a:\text{female}} e \in E) = 0.33$	demographic parity	$p(e \in \mathcal{G}_{a:\text{female}} e \in E, (S_e \cap S \neq \emptyset)) = 0.50$	equal opportunity
1	$\{\boxed{e_1}, e_3, e_4\}$	3	$1/3 \approx 0.33$	✓	$1/3 \approx 0.33$	✗
2	$\{\boxed{e_1}, \boxed{e_2}, e_3\}$	2	$2/3 \approx 0.67$	✗	$2/3 \approx 0.67$	✗
3	$\{\boxed{e_2}, e_3, e_4\}$	2	$1/3 \approx 0.33$	✓	$1/3 \approx 0.33$	✗
4	$\{\boxed{e_1}, e_3, \textcolor{red}{e_5}\}$	2	$1/3 \approx 0.33$	✓	$1/2 = 0.50$	✓
5	$\{\boxed{e_1}, \boxed{e_2}, e_4\}$	2	$2/3 \approx 0.67$	✗	$2/3 \approx 0.66$	✗

398 It is worth noting that merely recommending a fair team while neglecting its success measures is also undesirable, *e.g.*, a
 399 **team of nonpopular experts who fall short of accomplishing tasks. Hence,** and metrics of accuracy (utility) based on the team's
 400 **true label of success (✓)** ground-truth set of members should also be measured for a team recommender on top of fairness.

401 **Example 4.** To illustrate the evaluation of fairness and accuracy in recommended teams, we consider a small population of 6
 402 experts, where two are female $\mathcal{G}_{a:\text{female}} = \{\boxed{e_1}, \boxed{e_2}\}$ and 4 are male $\mathcal{G}_{a':\text{male}} = \{e_3, e_4, e_5, e_6\}$. The required skill set for a successful
 403 team is $S = \{s_1, s_2\}$, and only a subset of experts is qualified, i.e., their skill sets intersect with S . The *unseen* ground-truth
 404 team $E^* = \{\boxed{e_1}, e_3, e_4\}$ represents the actually successful team from the test set, while the example recommended teams E are
 405 generated by neural models for a successful team for the same skill requirements. Table 1 summarizes the expert pool, their
 406 gender, skills, qualifications, and prior group probabilities. Table 2 lists several candidate recommended teams of size top- $k = 3$,
 407 showing the recall (overlap) with the ground-truth team as an accuracy measure, the posterior proportion of each protected
 408 group in the team, and whether demographic parity and equal opportunity are satisfied. This example demonstrates the trade-off
 409 between accuracy and fairness. As seen, while the #1 recommendation achieves perfect accuracy with the ground-truth team,
 410 it violates equal opportunity. In contrast, while #4 satisfies demographic parity and equal opportunity, it comes at the cost of
 411 reduced accuracy. It also illustrates how posterior distributions can be used post-hoc to assess and, if necessary, adjust team
 412 recommendations to improve fairness while considering expert qualifications.

413 3.4 | Proposed Probabilistic Reranking Method

Let S be the subset of required skills and $f_\theta(S)$ is the team recommendation method estimated by a neural model that recommends an optimum subset of experts, E who collectively cover the required subset of skills S and are almost surely successful, i.e., $f_\theta(S) = E$ such that $(S, E)_{y=1}$. If E is *not* a fair team, i.e., $\mathbb{I}(f_\theta(S)) = \mathbb{I}(E) = 0$, our goal is to estimate a function $g : \mathcal{E} \rightarrow \mathcal{E}; g(E) = \textcolor{red}{E^*}$ such that:

$$\cancel{\mathbb{I}(E^*)} = \mathbb{I}(g(E)) = \mathbb{I}(g(f_\theta(S))) = 1 \quad (24)$$

414 We frame our reranking method based on *independent* Bernoulli trials of win/lose to find a fair team in the top- k ranked list
 415 of a model's prediction in Equation 5. Given pq as the desired **proportion distribution** of protected experts in a fair team and a
 416 significance level α , **which is selected based on the underlying domain**, we test, at each position, top- $\{1, \dots, k\}$, if the ranked list
 417 statistically significantly follows Bernoulli distribution with winning probability pq . Let $E_{r,k}$ be the first k experts of E ranked by
 418 a ranker r based on experts' probabilities in Equation 5 produced by a team recommendation method that estimates f_θ . Further,
 419 let a **protected attribute \mathcal{A}** whose values $\{a, a'\}$ split the expert set \mathcal{E} into \mathcal{G}_a as the disadvantaged group and $\mathcal{G}_{a'}$ as the advantaged
 420 group, respectively, *e.g.*, $\mathcal{G}_{a:\text{female}}$ and $\mathcal{G}_{a':\text{male}}$, $|E_{r,k}|_{\textcolor{red}{y}}$ be the current number of **protected** experts from the disadvantaged group

TABLE 3 Minimum number of required *disadvantaged* experts in the top- $k \in \{1, \dots, 10\}$ under demographic parity and equal opportunity in Examples 1 and 3. The probability of success pq is based on Propositions 2 and 19, leading to different minimum requirements across fairness notions and confidence levels. For equal opportunity, on a *per-team* basis, the prior distribution is obtained over qualified experts whose skill sets intersect with the team's required skill set S , and pq and \mathbb{F}^{-1} are computed accordingly.

fairness notion	$q=p(e \in \mathcal{G}_{afemale}) = 0.3$ (across dataset)	α	$\mathbb{F}^{-1}(\alpha, k, q)$									
			$k=1$	$k=2$	$k=3$	$k=4$	$k=5$	$k=6$	$k=7$	$k=8$	$k=9$	$k=10$
demographic parity	$q=p(e \in \mathcal{G}_{afemale}) = 0.3$ (across dataset) <td>0.50</td> <td>0</td> <td>0</td> <td>1</td> <td>1</td> <td>1</td> <td>2</td> <td>2</td> <td>2</td> <td>2</td> <td>3</td>	0.50	0	0	1	1	1	2	2	2	2	3
		0.10	0	0	0	0	0	0	1	1	1	1
		0.05	0	0	0	0	0	0	0	0	1	1
		0.01	0	0	0	0	0	0	0	0	0	0
equal opportunity	$q=p(e \in \mathcal{G}_{afemale} \mid S_e \cap S \neq \emptyset) = 0.5$ (per team) <td>0.50</td> <td>0</td> <td>1</td> <td>1</td> <td>2</td> <td>2</td> <td>3</td> <td>3</td> <td>4</td> <td>4</td> <td>4</td>	0.50	0	1	1	2	2	3	3	4	4	4
		0.10	0	0	0	1	1	1	2	2	2	3
		0.05	0	0	0	0	1	1	1	2	2	2
		0.01	0	0	0	0	0	0	1	1	1	1

TABLE 4 The minimum number of required disadvantaged experts in the top $k \in \{1, \dots, 10\}$; equivalently, the minimum number of successes with statistical confidence of 0.9 in k Bernoulli trials each with winning probability of $p = 0.6$.

α	p	k	$\mathbb{F}^{-1}(k)$
0.1	0.6	1	0
		2	0
		3	1
		4	1
		5	2
		6	2
		7	3
		8	3
		9	4
		10	4

421 in the $E_{r,k}$, and $\mathbb{F}(|E|_{ay}; |E|, pq)$ be the cumulative distribution function for a binomial probability of having $|E|_{ay}$ experts of
422 a **protected** the disadvantaged group in the predicted team via $|E|$ independent Bernoulli trials with **at**he winning rate pq . We
423 calculate **the** \mathbb{F} 's inverse function $\mathbb{F}^{-1}(\alpha; k, pq)$ to determine the minimum number of required protected experts in E from
424 top- $\{1, \dots, k\}$. Table 3 illustrates **thesample** values of $\mathbb{F}^{-1}(\alpha; k, pq)$ for top- $\{1, \dots, k = 10\}$. **We denote** $\mathcal{G}_{a_1} = \{e_1^{(1)}, \dots, e_1^{(l)}\}$
425 **as the set of** $|\mathcal{G}_a|$ **experts in the disadvantaged protected group (e.g., female or nonpopular experts).** Then, we rank experts of the
426 disadvantaged group using the **current** ranker r as $\mathcal{G}_a = \{e_1^{(a)}, e_2^{(a)}, \dots, e_{|\mathcal{G}_a|}^{(a)}\}$ and, as for reranking function $g(E)$, we propose a
427 new ranking r' based on the following:

$$\left\{ \begin{array}{ll} \hat{g}(e_i^{(k)}) = e_i^{(k)} & \\ g(e_k) = e_k; e_k \in \mathcal{E}; & \text{if } \mathbb{F}^{-1}(\alpha; k, pq) \leq |E_{r,k}|_{ay} \text{ no change required} \\ \\ \hat{g}(e_i^{(k)}) = e_1^{(1)}; \hat{g}(e_i^{(k+1)}) = e_1^{(2)}; \dots; \hat{g}(e_i^{(k+m-1)}) = e_1^{(m)} & \\ \\ g(e_k) = e_1^{(a)} \mid g(e_{k+1}) = e_2^{(a)} \mid \dots \mid g(e_{k+m-1}) = e_m^{(a)}; & \text{if } \mathbb{F}^{-1}(\alpha; k, pq) > |E_{r,k}|_{ay} \text{ insertion from ranked } \mathcal{G}_a \text{ till no change required} \end{array} \right. \quad (25)$$

428 where $m = \mathbb{F}^{-1}(\alpha; k, pq) - |E_{r,k}|_{ay}$ is the least number of **protected** experts from the disadvantaged group \mathcal{G}_a to be added to make
429 a team fair. Our method *inserts* the experts by shifting the experts down the list. For example, should a (male) expert in the fourth
430 position ($e_1^{(4)} e_4$) be replaced with the *most* qualified female expert in the seventh position ($e_0^{(7)} e_7^{(a)}$), the female expert would
431 be moved up to the fourth position ($g(e_1^{(4)}) = e_0^{(7)} g(e_4) = e_7^{(a)}$) and shift the list down such that the (male) expert in the fourth
432 position moves to the fifth ($e_1^{(5)} e_5$), and so on. Therefore, as we rerank, all experts are still ranked based on their qualifications. If
433 the number of disadvantaged experts up until the fourth position, i.e., $|E_{r,k=4}|_{ay}$, is greater than or equal to $\mathbb{F}^{-1}(\alpha; k = 4, pq)$,
434 sufficient disadvantaged experts have been inserted up to this position. Otherwise, m disadvantaged experts should be inserted

435 depending on the given notion of fairness. For equality-of opportunity, we select from *qualified* disadvantaged experts. However,
 436 for demographic parity, we overlook the qualification criteria and simply select from disadvantaged experts.

437 Regarding the role of the significance level α , suppose an *observed* recommendation contains x experts from the disadvantaged
 438 group. We perform a significance test with the null hypothesis $H_0 : x \sim \mathbb{F}(x; k = 10, q = 0.3)$ and compute the corresponding
 439 p -value. If the p -value $> \alpha$, the observation is considered statistically plausible under H_0 , and we therefore “fail to reject” the
 440 null hypothesis, treating the team as fair. Conversely, if the p -value $\leq \alpha$, the observation is deemed unlikely, leading to rejection
 441 of H_0 and the team being flagged as unfair. The choice of α directly controls the strictness of the fairness criterion. Larger values
 442 of α increase the likelihood of rejecting H_0 , requiring stronger alignment with the distribution. For instance, when $\alpha = 0.1$ and
 443 no disadvantaged experts are observed ($x = 0$) in a top- $k = 10$, the p -value is $\mathbb{F}(x = 0; k = 10, q = 0.3) = 0.028 < 0.1$, and the
 444 null hypothesis is rejected, flagging the team as unfair. In contrast, for $\alpha = 0.01$, the same observation yields $0.028 > 0.01$,
 445 and the null hypothesis is *not* rejected, resulting in the team being considered fair. From a mitigation perspective, larger values
 446 of α impose stricter fairness requirements, as more disadvantaged experts are needed for a team to pass the significance test.
 447 Smaller values of α relax this requirement and may not trigger mitigation even when the observed composition deviates from
 448 the expected proportion, as shown in Table 3 for $\alpha \in \{0.50, 0.1, 0.05, 0.01\}$. Meanwhile, the choice of α also controls the
 449 fairness trade-off with accuracy of the recommended experts (utility), allowing more conservative (e.g., $\alpha = 0.1$) vs. permissive
 450 ($\alpha = 0.5$) additions of experts from the disadvantaged group by avoiding unnecessary enforcement of proportion constraints and
 451 reducing utility loss while maintaining statistically grounded fairness.

452 To form a fair ranking of k experts, we assume there exist at least *k members from each protected group*. $k \times q$ experts from the
 453 disadvantaged group. To satisfy demographic parity, we require $k \times p(e \in \mathcal{G}_a)$ experts from the disadvantaged group, ensuring
 454 that the prior group distribution matches its posterior distribution among the top- k recommended experts for a successful team
 455 (Proposition 2). To satisfy equal opportunity, we require $k \times p(e \in \mathcal{G}_a | S_e \cap S \neq \emptyset)$ *qualified* from the disadvantaged group,
 456 so that the prior distribution of qualified experts matches its posterior distribution among the top- k recommendations for a
 457 successful team (Proposition 3). From datasets in real-world scenarios, as seen in Table 5, the average number of members in a
 458 team (team size) is 3.06, 1.88, 2.51 in dblp, imdb, and uspt, respectively, which is almost surely less than the number of
 459 disadvantage experts, i.e., female or nonpopular experts, in the entire datasets. We empirically evaluate our reranking method *for*
 460 *top-k=10, which still remains within practical reach*, on three large-scale datasets using three fairness metrics, namely $ndkl^109$,
 461 $skew^{36}$ and $expo^{107}$. Meanwhile, we evaluate the models’ accuracy by information retrieval metrics, including map and ndcg.

4 | EXPERIMENTS

462 In this section, we lay out the details of our experiments and findings to answer the following research questions:

463 **RQ1:** Does our proposed probabilistic reranking method mitigate unfair biases, including popularity bias and gender bias
 464 individually, in the recommended team of experts based on demographic parity and equality-of opportunity while maintaining
 465 the team’s likelihood of success?

466 **RQ2:** Does our proposed probabilistic reranking method outperform deterministic reranking methods in mitigating popularity
 467 and gender biases in view of demographic parity and equality-of opportunity?

468 **RQ3:** Does our proposed probabilistic reranking method effectively reduce bias while enhancing the exposure to success ratio,
 469 as measured by utility-aware exposure (expo), for disadvantaged groups, e.g., nonpopular and female experts?

470 **RQ4:** Is the effect of our proposed reranking method consistent across datasets from different domains?

4.1 | Datasets

471 We evaluate our proposed method on three well-known large-scale benchmark datasets in team recommendation literature
 472 including dblp^{25,27,24,87}, imdb^{27,88,56}, and uspt^{91,89}. In dblp, each team is a publication in computer science consisting of
 473 authors as the experts and the fields of study (fos) as the skills. In imdb, each instance is a movie. We consider each movie as a
 474 team whose members are the cast and crew, and the movies’ genres are the teams’ skills. The choice of imdb in team formation
 475 literature is not to be confused with its use cases in review analysis research; herein, the goal is to form a team of casts and
 476 crews for a *movie production* as opposed to a movie recommendation^{88,56}. In uspt, each instance is a patent issued by the
 477 United States Patents and Trademarks consisting of inventors (experts) and subcategories (skills). Table 5 reports statistics on the
 478 datasets. From Figure 1, male experts are dominating teams while female experts have participated sparingly in all datasets.
 479

TABLE 5 Statistics for the benchmark datasets utilized in our experiments as well as mapping of data properties to instances of team.

	dblp	imdb	uspt
success $y = 1$	published	produced	issued
#teams $ T $	publications 4,877,383	movies 507,034	patents 7,068,508
#experts $ \mathcal{E} $	authors 5,022,955	cast'ncrew 876,981	inventors 3,508,807
#skills $ \mathcal{S} $	fields of study 89,504	genres, subgenres 28	classes, subclasses 241,961
avg #experts in teams	3.06	1.88	2.51
avg #teams per expert	23.02%	62.45%	44.69%
%popular experts (avg)	31.30%	42.60%	31.40%
%nonpopular experts (avg)	68.70%	57.40%	68.60%
%female experts	14.20%	12.30%	13.80%
%male experts	85.80%	87.70%	86.20%

481 Also, from Figure 2, all datasets suffer from the long tail problem in the distributions of teams over experts, i.e., many experts
 482 (researchers in dblp, cast and crew in imdb, and inventors in uspt) have participated in very few teams (papers in dblp,
 483 movies in imdb, and inventions in uspt).

484 4.2 | Dataset Labeling Criteria Forming Protected Groups

485 **Success Labels:** Benchmark datasets in team recommendation literature consist of successful teams only, missing unsuccessful
 486 ones. For instance, the dblp lacks unsuccessful submissions. Further, what it means for a team to be successful has remained
 487 controversial. For instance, in the movie industry, it is debatable whether a movie's success should be measured based on its
 488 immediate reception by the people (box office) or critical reviews (ratings) within a long span of time. In the absence of explicit
 489 labels for unsuccessful teams, neural team recommendation methods presume *all* instances of teams in the training dataset as
 490 successful (positive samples) and proceed with the training procedure.

491 **Gender Labels:** Contrary to popularity, gender is self-identified. While uspt dataset includes gender labels, other training
 492 datasets lack gender labels in part or whole. In imdb, although we inferred the gender of some cast and crew by their role
 493 identified as actor or actress, gender labels for other experts were missing. In dblp, no gender label for the experts has been
 494 provided. Therefore, we utilized genderize¹⁴¹, a crowd-based system that predicts a gender based on the given name of the
 495 experts, for dblp as well as those that are missing in imdb. Meanwhile, we recognize that predicting gender using name-to-
 496 gender services such as genderize might systematically mislabel certain demographic groups due to cultural, linguistic, and
 497 regional variations. For example, names such as '*Andrea*' (typically male in Italy but female in English-speaking countries),
 498 '*Sasha*' (male in Russia but commonly female in North America), and '*Kim*' (gender-neutral in East Asia but often inferred as
 499 female in Western countries) are frequently misclassified. Hence, our results should be interpreted with this limitation in mind.
 500 As seen in Figure 1, datasets are heavily biased toward male experts. Specifically, dblp has a male-to-female ratio of 0.858 to
 501 0.142, imdb has a slightly different ratio of 0.877 to 0.123 and uspt has a ratio of 0.862 to 0.138.

502 **Popularity Labels:** Defining popularity could be controversial. To avoid varied interpretations, we followed social science
 503 and recommender system literatures, where the popularity status of an expert can be objectively measured based on the num-
 504 ber of teams the expert has participated in, referred to as *sociometric* popularity. Further, although an expert's participation
 505 in many teams, e.g., research papers in dblp or movies in imdb, may not necessarily indicate popularity from the people's
 506 perspectives, repetition of the expert in many training samples of teams from the neural model's perspective does.

507 Accordingly, we can adopt two alternatives, as shown in Figure ■ *i*) an expert is popular if the expert participated in more
 508 than the average number of teams per expert over the entire dataset, and nonpopular otherwise (avg), or *ii*) an expert is popular
 509 if she belongs to the *short head* in the 2-d curve of the distribution of experts in teams, and nonpopular otherwise. We split the
 510 curve into *short head* and *long tail* based on equal area under the curve (auc). From Section 3.3.1, among the two options for
 511 splitting experts into popular and non-popular groups based on the long-tail distribution, namely avg and auc, we opt for avg
 512 criterion, labeling experts above the average number of teams an expert participates as popular. In contrast to the auc criterion,
 513 which identifies popular experts as those located in the first half of the area under the curve (head), we favor the avg since it
 514 provides a simpler, more transparent, and easily reproducible threshold, while avoiding sensitivity to the exact shape of the
 515 distribution required by the auc. For the dblp dataset, the average stands at 23.02 teams, 62.45 teams for the imdb dataset,
 516 and 44.69 teams for the uspt dataset. Therefore, in dblp, the proportion of popular to nonpopular experts becomes 0.313 to
 517 0.687, in imdb, it is 0.426 to 0.574 and for uspt it stands at 0.314 to 0.686.

518 **4.3 | Baselines**519 **4.3.1 | Neural Team Recommendation**

520 We compare the impact of our proposed probabilistic reranking method on mitigating neural models' biases using the state-
 521 of-the-art variational Bayesian neural network (bnn)^{25,27,24} with a single hidden layer of size $d = 128$, leaky relu as the
 522 activation function for the hidden layer, and Kullback-Leibler (KL) divergence as the optimizer. For the input layer, as detailed
 523 in Section 3.1, we used sparse occurrence vector representations (one-hot encoded) of skills of size $|S|$ as well as pretrained
 524 dense vector representations ($-emb$)²⁶. The output layer is the sparse occurrence vector representations (one-hot encoded) of
 525 experts of size $|S|$ and $|\mathcal{E}|$, respectively. We randomly select 15% of teams for the test set and perform 5-fold cross-validation
 526 on the remaining teams for model training over 20 epochs ~~that results, resulting~~ in one trained model per ~~each~~ fold. Given a
 527 team (S, E) from the test set, we select the top- $k \in \{5, 10\}$ =100 experts with the highest probabilities as the recommended team
 528 $E = f_{\theta}(S)$ by the model of each fold. Although the average team size in the datasets is small (between 1.88 and 3.06), evaluating
 529 fairness-aware reranking at such small cardinalities can lead to over- or underestimation of the fairness metrics. For example,
 530 if the desired ratio between female and male experts is 0.3 to 0.7, then for a team of size $k=2$, this corresponds to 0.6 female
 531 and 1.4 male members and feasible splits are either (0 female, 2 male) or (1 female, 1 male), yielding ratios of 0 or 0.5 and
 532 deviates substantially from the target 0.3. Hence, it can result in large inaccuracies when reporting fairness metrics. Similarly,
 533 for a team of size 3, the expected split is 0.9 and 2.1, with feasible splits (0 female, 3 male) or (1 female, 2 male), giving a ratio
 534 of approximately 0.33. As shown, using a larger k allows for a more accurate calculation of posterior distributions and reduces
 535 rounding errors and large deviations. On the other hand, as noted, real-world teams are often of size 2 to 3 members. To balance
 536 the need for meaningful posterior calculation with real-world team sizes, we therefore adopt top- $k \in \{5, 10\}$.

537 **4.3.2 | Fairness-aware Reranking**

538 Our fairness-aware reranking baselines include three deterministic greedy reranking algorithms det-greedy, det-cons, and
 539 det-relaxed by Geyik et al.³⁶, ~~detailed below~~, as well as our proposed probabilistic reranking method with the significance
 540 level $\alpha \in \{0.10, 0.05\}$. Our probabilistic method builds upon the framework of Zehlike et al.³⁴ and adapts it for the team
 541 recommendation task, introducing necessary modifications to handle team compositions by altering the reranking procedure.
 542 Consequently, the original method cannot serve as a separate baseline, as it is effectively a trivial special case of our team-level
 543 adaptation.

- 544 • **det-greedy (probability-driven, potentially infeasible):** A deterministic greedy reranking algorithm with prefix minimum
 545 and maximum number constraints. At each rank position k , det-greedy considers experts ranked by their selection score
 546 probabilities produced by the underlying team recommendation model. For each value a of a protected attribute \mathcal{A} , the
 547 algorithm maintains a minimum required number $[k|E_{r,k}]_a$ and a maximum allowed number $[k|E_{r,k}]_a$ of selected experts
 548 with attribute value a in the top- k list. If the current number of experts from some attribute value is below its minimum
 549 required number, det-greedy selects the expert with the highest probability among those attribute values. Otherwise, it
 550 selects the expert with the highest probability among attribute values whose maximum allowed number has not yet been
 551 reached. While this approach maximizes probabilities at each step, it may lead to infeasibility in later positions, meaning
 552 that it could become impossible to satisfy the minimum or maximum number requirements for some attribute values in
 553 future ranks if earlier selections over-represent a particular protected value. Expert probabilities are the primary selection
 554 criterion whenever the number constraints permit.
- 555 • **det-cons (constraint-driven, probability-agnostic):** A deterministic greedy reranking algorithm that enforces prefix
 556 number constraints. When all protected values satisfy their minimum numbers at rank k , det-cons ignores expert probabilities
 557 (utility) and selects the protected value whose remaining allowance to its maximum number is smallest, i.e., the value that
 558 is closest to reaching its maximum allowed number of experts. This ensures that future positions in the ranking will remain
 559 valid with respect to the maximum number constraints
- 560 • **det-relaxed (constraint-first, probability-second):** A probability-aware relaxation of det-cons algorithm. At each rank
 561 k , det-relaxed first identifies the protected value that is closest to reaching its maximum allowed number of experts in
 562 the ranking as in det-cons; at this step, it ignores the experts' probabilities (utility). Among the available experts of that

TABLE 6 Expected number of female experts at each top- k by the probabilistic reranking method vs. min. and max female expert allocations by the deterministic baselines for fairness according to demographic parity. The prior distribution of female experts in the dataset is 0.3

	expected number of females	k=1	k=2	k=3	k=4	k=5	k=6	k=7	k=8	k=9	k=10
probabilistic	$F^{-1}(\alpha = 0.1, k, p = 0.3)$	0	0	0	0	0	0	1	1	1	1
deterministic	min=[0.3 × k]	0	0	0	1	1	1	2	2	2	3
	max =[0.3 × k]	1	1	1	2	2	3	3	3	3	3

563 protected value, det-relaxed then selects the expert with the highest recommendation probability produced by the team
564 recommendation method.

565 Existing deterministic reranking methods, such as det-greedy, det-cons, and det-relaxed, have notable limitations despite
566 prioritizing fairness in different ways. det-greedy prioritizes expert probabilities (utility) at each step; however, because the
567 minimum and maximum numbers for protected groups are computed deterministically, it can become infeasible, potentially
568 violating fairness constraints in later positions. det-cons and det-relaxed explicitly prioritize fairness over utility, often ignoring
569 probabilities in the main selection step and favoring protected groups to satisfy minimum and maximum requirements, which
570 can lead to selecting lower-probability experts. In contrast, our probabilistic reranking method computes the required number of
571 protected members at each top- k using a binomial distribution, ensuring that the minimum required number of experts from each
572 protected group is always available. Furthermore, selections are always guided by utility, so that when an expert from a protected
573 group must replace an existing candidate, the algorithm chooses the one with the highest probability, thereby preserving overall
574 utility while mitigating bias.

575 As shown in Tables 14, Table 10 and 12, all methods, including our baselines, effectively reduce bias (the green color in the
576 fairness metrics columns for skew and ndkl highlights the substantial improvement after reranking), but unlike the baselines
577 as expected, our method maintains utility despite reducing bias (green cell for utility metrics, map and ndcg, as opposed to the
578 red cell for the baselines), demonstrating that it effectively balances the fairness-accuracy trade-off typically encountered in
579 reranking scenarios.

580 4.4 | Evaluation Strategy

581 To measure the effectiveness of our proposed method, it is essential to evaluate fairness in the teams to ensure equitable treatment
582 of all individuals and prevent systematic discrimination against protected groups. Measuring fairness metrics before and
583 after team recommendation helps identify potential biases in the recommendation algorithm, quantifies the effectiveness of
584 fairness interventions, and provides transparency about how well the system promotes fairness. These evaluations also help
585 balance different notions of fairness and demonstrate compliance with ethical guidelines or organizational diversity goals while
586 maintaining accountability in the team recommendation process. Team utility must be considered alongside fairness because
587 teams ultimately need to accomplish tasks effectively. Measuring utility before and after fairness interventions is mandatory to
588 understand potential performance trade-offs, and identify possible performance improvements through diversity, and demonstrate
589 to stakeholders that fairness can be achieved while maintaining team effectiveness. Hence, we measure fairness and utility both
590 before and after applying our methodologies to our baselines.

591 4.4.1 | Before Mitigating Bias

592 To answer our research questions, we evaluate the efficacy of the model in recommending *correct* experts for each team of our
593 test set by comparing the ranked list of experts, predicted by the model of each fold, with the observed subset of experts E and
594 report the average performance of models on all folds in terms of information retrieval metrics including mean average precision
595 (map) and normalized discounted cumulative gain (ndcg) at top- $k \in \{5, 10\}$ =10, as explained in Section 4.4.3. Furthermore, to
596 assess the fairness of the predicted teams, we report the average fairness metrics, including normalized discounted Kullback-
597 Leibler (ndkl)¹⁰⁹, skew³⁶, and expo¹⁰⁷ for popularity and gender attributes with respect to demographic parity and equality
598 of opportunity, as formalized in Section 4.4.3. While skew is a symmetric metric to measure the symmetrical distribution of
599 data among protected attributes, ndkl is an asymmetric measure of differences between the actual and desired distributions of

protected attributes. For both of these metrics, the closer the value to 0, the more unbiased the distribution. In contrast to `ndkl` and `skew` that are not utility-aware, or in other words, they will not consider utility in their evaluations, `expo` calculates the exposure of different protected groups with respect to their utility.

603 4.4.2 | After Mitigating Bias

Given the predicted ranked list of experts \hat{E} by the model of each fold for the observed subset of experts E for a team of the test set, we apply fairness-aware reranking methods on \hat{E} to produce an unbiased ranked list of experts $\hat{g}(\hat{E})$. We then evaluate the new reranked list in terms of information retrieval metrics and fairness metrics. We presume that fairness-aware reranking baselines improve the fairness metrics without discounting the informational retrieval metrics.

In total, we compare $\{\text{bnn}, \text{bnn-emb}\}$ baselines for $\{\text{popularity}, \text{gender}\}$ protected attributes with respect to $\{\text{demographic parity, equality-of opportunity}\}$ notions of fairness *before* and *after* applying fairness-aware reranking methods $\{\text{det-greedy, det-cons, det-relaxed, our method}\}$ in terms of $\{\text{map, ndcg}\}$ information retrieval metrics and $\{\text{skew, ndkl, expo}\}$ fairness metrics on $\{\text{dblp, imdb, uspt}\}$ datasets.

612 4.4.3 | Fairness and Utility Metrics

Let (S, E) a team of experts E for the required set of skills S from the test set, we compare the top- k ranked list of experts, predicted by the model of each fold for the input skills S , i.e., $f_\theta(S)$, with the observed subset of experts E and report the average performance of models on all folds in terms of utility metrics (the higher, the better) as formalized below.

1) Mean Average Precision (map)

$$\text{ap}(k) : \frac{\sum_{i=1}^k \text{pr}(i) \times \delta_E(i)}{|E \cap f_\theta(S)|} \quad (26)$$

where $\text{pr}(k) = \frac{|E \cap f_\theta(S)|}{k}$ is the precision, i.e., how many of the k predicted experts are correctly identified from the test instance of the team E and $\delta_e(i)$ returns 1 if the i -th predicted expert is in E . Finally, we report the mean of average precisions (map) on all test instances of teams.

619 2) Normalized Discounted Cumulative Gain (ndcg)

$$\text{dcg}(k) = \sum_{i=1}^k \frac{\text{rel}(i)}{\log(i+1)} \quad (27)$$

where $\text{rel}(i)$ captures the degree of relevance for the predicted expert at position i . In our problem setting, however, all members of a test team are considered of the same importance. Therefore, $\text{rel}(i) = 1$ if $i \in E$ and 0 otherwise, and Equation (27) becomes:

$$\text{dcg}(k) = \sum_{i=1}^k \frac{\delta_E(i)}{\log(i+1)} \quad (28)$$

This metric can be *normalized* relative to the ideal case when the top- k predicted experts include members of the test team E at the lowest possible ranks, i.e.,

$$\text{ndcg}(k) = \frac{\sum_{i=1}^k \frac{\delta_E(i)}{\log(i+1)}}{\sum_{i=1}^{|E|} \frac{1}{\log(i+1)}} \quad (29)$$

Utility metrics are, however, oblivious to the protected attributes of experts, and hence, overlook whether the set of top- k predicted experts is a fair team (Section 3.3). To evaluate fairness, we use well-known fairness metrics as follows:

622 **1) Normalized Discounted KL Divergence (ndk1)**¹⁰⁹, which builds upon the foundation of Kullback-Leibler (KL) diver-
 623 gence to measure the expectation of the logarithmic difference between two discrete probability distributions, (the lower,
 624 the better) with being 0 in the ideal equal distributions. However, it advances a step further by incorporating a discounting
 625 factor, which allows it to assign varying levels of importance to different elements within the distributions being com-
 626 pared. This discounting is particularly valuable in scenarios where the order or priority of elements matters, as a result
 627 of which ndk1 has been extensively employed in recommendation systems and information retrieval^{142,143,36,144,145,35,146}.
 628 Additionally, ndk1 includes a normalization component, which scales the results to a more interpretable range and facil-
 629 itates comparisons across different baselines. Formally, let $p = \frac{|\mathcal{E}_{r,i}|}{i}$ be the distribution of a protected group in the top- i
 630 predicted experts by a ranker r , e.g., the proportions of nonpopular or female experts, and q the ideal fair distribution for a
 631 test instance of a team (S, E), the KL divergence of q from p is:

$$k\ell(p\|q) = \sum_{i=1}^k p(i) \log \frac{p(i)}{q(i)} \quad (30)$$

632 where q can be manually set, like 50%, or calculated based on the overall distribution (proportion) of the protected group in
 633 the entire dataset, i.e., $q = \frac{|\mathcal{E}_a|}{|\mathcal{E}|}$. This metric has a minimum value of 0 when both distributions are identical up to position
 634 i . A higher value indicates a greater divergence between the two distributions, and the metric is always non-negative. We
 635 report the *normalized discounted cumulative KL-divergence* (ndk1)³⁶:

$$\text{ndk1}(p) = \frac{\sum_{i=1}^{|\mathcal{E}|} \frac{1}{\log(i+1)} k\ell(p\|q)}{\sum_{i=1}^{|\mathcal{E}|} \frac{1}{\log(i+1)}} \quad (31)$$

636 **Example 5.** Ndk1@k incorporates the positions at which protected experts appear in the ranking. Specifically, ndk1
 637 aggregates the KL-divergence between the posterior and reference group distributions computed at each prefix of the
 638 ranking, assigning higher weight to top positions. Using the same top-10 ranking, suppose 3 female experts from positions
 639 {2, 5, 9}. Using demographic parity, the reference distribution is $p(e \in G_{a:\text{female}}) = \frac{30}{100} = 0.3$, and at top-2, one female
 640 expert appears, yielding the posterior distribution $q_2 = \frac{1}{2} = 0.5$; and the KL-divergence ($p\|q_2$) is therefore positive;
 641 $k\ell(p\|q_2) = p(e \in G_{a:\text{female}}) \times \log \frac{p(e \in G_{a:\text{female}})}{q_2(a)} + p(e \in G_{a':\text{male}}) \times \log \frac{p(e \in G_{a':\text{male}})}{q_2(a')} = 0.3 \times \log(\frac{0.3}{0.5}) + 0.7 \times \log(\frac{0.7}{0.5}) = 0.081$.
 642 At top-5, two female experts appear, giving $q_5 = \frac{2}{5} = 0.4$ which is closer to the reference and results in a smaller divergence,
 643 i.e., $k\ell(p\|q_5) = 0.3 \times \log(\frac{0.3}{0.4}) + 0.7 \times \log(\frac{0.7}{0.6}) = 0.022$. At top-10, the posterior distribution equals the reference,
 644 $q_{10} = \frac{3}{10} = p$, and the KL-divergence becomes 0. Near-zero ndk1 values therefore indicate fairness under the chosen
 645 notion, while larger values reflect increasing unfairness.

646 **2) Skew@k**³⁶ is the logarithmic ratio of (1) the proportion of items, herein the experts, from a protected group among the
 647 top- k predicted experts to (2) the ideal fair proportion for that group. Similar to ndk1, given $p = \frac{|\mathcal{E}_{r,i}|}{i}$ as the distribution
 648 of a protected group in the top- i predicted experts by a ranker r , and $q = \frac{|\mathcal{E}_a|}{|\mathcal{E}|}$ the ideal fair distribution, without loss of
 649 generality to any desired distribution for a test instance of a team (S, E):

$$\text{skew}@i(r) = \log_e \left(\frac{p}{q} \right) \quad (32)$$

650 A negative skew@i corresponds to a lesser than desired representation of experts with the protected group in the top- k
 651 results, while a positive skew@i corresponds to favoring such experts. The log makes this metric symmetric around zero
 652 with respect to ratios for and against a specific protected group and is particularly useful for assessing whether a ranker
 653 tends to favor certain protected groups disproportionately¹⁴⁷.

654 **Example 6.** Skew@k quantifies representation bias as the logarithmic ratio between the observed proportion of protected
 655 experts in the top-k positions and an ideal reference proportion. Same as Example 5, using the same top-10 ranking where 3
 656 female experts appear at positions {2, 5, 9}, reference distribution under demographic parity is $p(e \in G_{a:\text{female}}) = \frac{30}{100} = 0.30$,
 657 and the posterior distribution for a protected expert in cutoff top-2, top-5 and top-10 are $q_2 = \frac{1}{2} = 0.5$, $q_5 = \frac{2}{5} = 0.4$
 658 and $q_{10} = \frac{3}{10} = 0.3$, respectively. The resulting skew@2 = $\log \frac{q_2}{p} = \log(\frac{0.5}{0.3}) = 0.511$, skew@5 = $\log(\frac{q_5}{p}) = \log(\frac{0.4}{0.3}) = 0.288$, and skew@10 = $\log(\frac{q_{10}}{p}) = \log(\frac{0.3}{0.3}) = 0$. In other words, skew@k captures the magnitude of
 659 representation imbalance at a given cutoff, but unlike ndk1, it overlooks positional importance within the ranking.
 660

661 3) **Utility-aware Exposure (expo)**¹⁰⁷ measures the ratio of exposure to success across different protected groups in the top- k
 662 predicted experts^{20,148,149,34,150,151,152,153,154,155}. In recommender systems, exposure for each protected group is defined as
 663 the expected probability that an expert of a protected group will be presented at top- k position. This metric quantifies the
 664 likelihood of visibility for each member of protected group and provides a measure of how equitably exposure is distributed
 665 across different protected groups. Given the top- k ranked list of predicted experts for a team E, the exposure for an expert is
 666 calculated as:

$$\text{expo}(e) = \frac{1}{\log(i+1)}; e \in E \quad (33)$$

667 The simplest fair exposure among groups is that the average exposures of the experts in protected groups are equal. Given a
 668 protected attribute \mathcal{A} $a = \{a_1, \dots, a_n\}$, the average exposure for the experts of a protected group \mathcal{G}_a based on a protected
 669 attribute value a_i , e.g., female experts $\mathcal{G}_{a:\text{female}}$ vs. male experts $\mathcal{G}_{a:\text{male}}$, at the top- k :

$$\mu_{\text{expo}}(a_i) = \frac{1}{|\mathcal{E} \cap \mathcal{G}_a|} \sum_{e \in \mathcal{E} \cap \mathcal{G}_a} \text{expo}(e) \quad (34)$$

670 The expected utility of an expert in position-based ranking models can be determined by the probability of the expert
 671 appearing in a given position. To integrate utility in the exposure metric, an average probability score over experts of a
 672 protected group is also calculated as:

$$\mu_{\text{utility}}(a_i) = \frac{1}{|\mathcal{E} \cap \mathcal{G}_a|} \sum_{e \in \mathcal{E} \cap \mathcal{G}_a} v_E(e) \quad (35)$$

673 where v_E is a vector of probabilities in Equation 5 based on which a ranker select the top- k predicted experts as the
 674 recommended team. This is a form of group fairness that considers the utility associated with experts. The exposure value
 675 for a protected group is the ratio of average exposure values and average probability scores for a protected group, as follows:

$$\text{expo}(a_i) = \frac{\mu_{\text{expo}}(a_i)}{\mu_{\text{utility}}(a_i)} \quad (36)$$

676 Finally, the overall expo value is calculated for a protected attribute based on the ratio of exposure value for a pair of
 677 protected groups as:

$$\text{expo}(\mathcal{A}) = \frac{\text{expo}(a_f)}{\text{expo}(a_m)} \quad (37)$$

678 **Example 7.** Utility-aware exposure evaluates whether experts from a disadvantaged group receive ranking visibility
 679 proportional to their expected utility. We continue with the same top-10 ranking as in Examples 5 and 6, where 3 female
 680 experts appear at positions $\{2, 5, 9\}$. Suppose that the output probabilities (utilities) assigned by a team recommendation
 681 model to these experts are 0.95, 0.80 and 0.65, respectively. Exposure assigns higher importance to earlier positions in
 682 the ranking through a position-based weighting function. By Equation 34 the average exposure of the female experts is
 683 $\mu_{\text{expo}}(a : \text{female}) = \frac{1}{3}(\frac{1}{\log 3} + \frac{1}{\log 6} + \frac{1}{\log 10}) = 0.634$. Then by Equation 36 the exposure value for each team is then
 684 obtained by normalizing average exposure by average utility, i.e., $\mu_{\text{utility}}(a : \text{female}) = \frac{1}{3}(0.95 + 0.80 + 0.65) = 0.8$
 685 and $\text{expo}(a : \text{female}) = \frac{\mu_{\text{expo}}(a)}{\mu_{\text{utility}}(a)} = \frac{0.634}{0.8} = 0.793$. The average exposure of the team is computed similarly over the
 686 remaining 7 positions. The same computation is performed for the advantaged male experts, who occupy the remaining
 687 seven positions $\{1, 3, 4, 6, 7, 8, 10\}$. Using the same position-based exposure weights, their average exposure is $\mu_{\text{expo}}(a :
 688 \text{male}) = \frac{1}{7}(\frac{1}{\log 2} + \frac{1}{\log 4} + \frac{1}{\log 5} + \frac{1}{\log 7} + \frac{1}{\log 8} + \frac{1}{\log 9} + \frac{1}{\log 11}) = 0.721$. Assuming that the model output probabilities
 689 (utilities) of these seven experts are 0.97, 0.92, 0.91, 0.88, 0.82, 0.80, 0.70, the average utility of the male experts is:
 690 $\mu_{\text{utility}}(a : \text{male}) = \frac{1}{7}(0.97 + 0.92 + 0.91 + 0.88 + 0.82 + 0.80 + 0.70) = 0.86$, and the exposure value for them is
 691 $\text{expo}(a : \text{male}) = \frac{\mu_{\text{expo}}(a)}{\mu_{\text{utility}}(a)} = \frac{0.721}{0.86} = 0.84$. By Equation 37, the overall exposure value for the gender protected attribute is
 692 $\text{expo}(\text{gender}) = \frac{\text{expo}(a : \text{female})}{\text{expo}(a : \text{male})} = \frac{0.793}{0.84} = 0.94$. Here, $\text{expo}(a) < 1$ shows that the female (disadvantaged) experts receive
 693 slightly less exposure relative to their utility compared to male (advantaged) experts. Under demographic parity, fairness
 694 corresponds to $\text{expo}(a) = 1$, indicating that both groups should receive exposure proportional to their utility, independent
 695 of group membership. For equality of opportunity, the same computation is performed but restricted to *qualified* experts

696 only. Deviations of $\text{exp}(\alpha)$ from 1 indicate disparities in visibility relative to utility and therefore violations of the
 697 corresponding fairness notion. In both cases, higher-ranked positions contribute more heavily to exposure, making the
 698 metric sensitive to where experts of the disadvantaged group appear in the ranking.

T A B L E 7 Average performance of 5-fold neural models on test set on `dblp` dataset. For the metrics, `ndkl`, the lower the better (\downarrow), `skew`, the closer to 0 the better ($\rightarrow 0$), and `map` and `ndcg`, the higher the better (\uparrow).

		%ndkl	%ndkl	skew before $\rightarrow 0$		skew after $\rightarrow 0$		%map ¹⁰	%ndcg ¹⁰
		before \downarrow	after \downarrow	nonprotected	protected	nonprotected	protected	$\Delta \uparrow$	$\Delta \uparrow$
popularity, demographic parity									
bnn	det-cons	14.64				0.64	-0.54	-0.28	-0.58
	det-greedy	14.64		1.13		0.64	-0.54	-0.28	-0.58
	det-relaxed	18.31				0.64	-0.53	-0.28	-0.58
	our method	19.71				0.26	-0.15	0.00	0.00
bnn-emb	det-cons	14.09				0.62	-0.51	-0.28	-0.58
	det-greedy	14.09		1.14		0.62	-0.51	-0.28	-0.58
	det-relaxed	17.65				0.61	-0.50	-0.28	-0.58
	our method	19.61				0.26	-0.15	0.00	0.00
popularity, equality of opportunity									
bnn	det-cons	13.12				0.57	-0.51	-0.28	-0.58
	det-greedy	13.16		1.05		0.57	-0.51	-0.28	-0.58
	det-relaxed	16.15				0.57	-0.50	-0.28	-0.58
	our method	18.96				0.24	-0.16	0.00	0.00
bnn-emb	det-cons	12.65				0.55	-0.48	-0.28	-0.58
	det-greedy	12.67		1.06		0.55	-0.48	-0.28	-0.58
	det-relaxed	15.63				0.55	-0.47	-0.28	-0.58
	our method	18.39				0.25	-0.16	0.00	0.00
gender, demographic parity									
bnn	det-cons	4.92				-0.07	0.39	-0.28	-0.58
	det-greedy	3.72		-0.08		-0.07	0.39	-0.28	-0.58
	det-relaxed	6.52				0.00	-0.20	-0.28	-0.58
	our method	8.39				0.00	-0.11	0.00	0.00
bnn-emb	det-cons	4.97				-0.07	0.37	-0.28	-0.58
	det-greedy	3.59		-0.06		-0.07	0.37	-0.28	-0.58
	det-relaxed	4.92				-0.04	0.08	-0.28	-0.58
	our method	6.83				-0.03	0.13	0.00	0.00
gender, equality of opportunity									
bnn	det-cons	9.19				-0.13	0.86	-0.28	-0.58
	det-greedy	7.70		-0.14		-0.13	0.86	-0.28	-0.58
	det-relaxed	9.53				-0.13	0.85	-0.28	-0.58
	our method	18.97				-0.14	0.88	0.00	0.00
bnn-emb	det-cons	9.24				-0.13	0.86	-0.28	-0.58
	det-greedy	7.61		-0.11		-0.13	0.86	-0.28	-0.58
	det-relaxed	10.16				-0.13	0.85	-0.28	-0.58
	our method	15.93				-0.11	0.76	0.00	0.00

699 4.5 | Results

700 We report the comparative experimental results on three benchmark datasets `dblp`, `imdb`, and `uspt` in Tables 14, 10 and 12,
 701 respectively. Our analysis reveals several key findings. Foremost, we observe that neural team recommendation baselines
 702 exhibit significant biases with respect to two protected attributes: popularity (favoring already well-known experts) and gender
 703 (showing systematic under-representation of female experts). Before applying our debiasing reranking method, these baselines
 704 demonstrated a clear tendency to amplify the pre-existing biases in the data. Specifically, experts with a high volume of papers in
 705 `dblp`, many movies in `imdb`, and patents in `uspt` would be disproportionately recommended, while qualified experts with
 706 lower visibility were systematically overlooked. Similarly, the gender distribution in the recommended teams was significantly
 707 skewed, indicating algorithmic bias rather than a mere reflection of domain demographics. In terms of `ndkl` and `skew` metrics,

TABLE 8 Average performance of 5-fold neural models on test set on dblp dataset. For the metrics, ndkl, the lower the better (\downarrow), expo, the closer to 1 the better ($\rightarrow 1$), skew, the closer to 0 the better ($\rightarrow 0$), and map and ndcg, the higher the better (\uparrow).

		%ndkl \downarrow		expo $\rightarrow 1$		skew before $\rightarrow 0$				skew after $\rightarrow 0$		%map10	%ndcg10
		before	after	before	after	protected disadvantaged	nonprotected advantaged	protected disadvantaged	nonprotected advantaged	$\Delta \uparrow$	$\Delta \uparrow$		
popularity, demographic parity													
bnn	det-cons		14.64		2.43			-0.54	0.64	-0.28	-0.58		
	det-greedy		14.64		2.75		-19.97	1.13	-0.54	0.64	-0.28	-0.58	
	det-relaxed	109.56		0.26	2.24			-0.53	0.64	-0.28	-0.58		
	our method $\alpha=0.10$		19.71		1.01			-0.15	0.26	0.00	0.00		
	our method $\alpha=0.05$		22.25		0.99			-0.16	0.25	0.00	0.00		
bnn-emb	det-cons		14.09		2.55			-0.51	0.62	-0.28	-0.58		
	det-greedy		14.09		2.55		-20.75	1.14	-0.51	0.62	-0.28	-0.58	
	det-relaxed	110.31		0.23	2.35			-0.50	0.61	-0.28	-0.58		
	our method $\alpha=0.10$		19.61		1.03			-0.15	0.26	0.00	0.00		
	our method $\alpha=0.05$		22.16		1.01			-0.17	0.29	0.00	0.00		
popularity, equality-of opportunity													
bnn	det-cons		13.12		2.44			-0.51	0.57	-0.28	-0.58		
	det-greedy		13.16		2.44		-19.92	1.05	-0.51	0.57	-0.28	-0.58	
	det-relaxed	102.01		0.26	2.26			-0.50	0.57	-0.28	-0.58		
	our method $\alpha=0.10$		18.96		1.01			-0.16	0.24	0.00	0.00		
	our method $\alpha=0.05$		22.61		0.99			-0.18	0.27	0.00	0.00		
bnn-emb	det-cons		12.65		2.58			-0.48	0.55	-0.28	-0.58		
	det-greedy		12.67		2.58		-20.62	1.06	-0.48	0.55	-0.28	-0.58	
	det-relaxed	102.85		0.23	2.39			-0.47	0.55	-0.28	-0.58		
	our method $\alpha=0.10$		18.39		1.03			-0.16	0.25	0.00	0.00		
	our method $\alpha=0.05$		22.52		1.01			-0.18	0.28	0.00	0.00		
gender, demographic parity													
bnn	det-cons		5.90		0.86			-0.63	0.07	-0.28	-0.58		
	det-greedy		5.52		5.21	0.83	-0.20	0.02	-0.63	0.07	-0.28	-0.58	
	det-relaxed			1.01	5.21	0.83		-0.63	0.07	-0.28	-0.58		
	our method $\alpha=0.10$				5.12	0.98		-0.03	0.00	0.00	0.00		
	our method $\alpha=0.05$				5.27	0.98		-0.08	0.00	0.00	0.00		
bnn-emb	det-cons		5.80		0.78			-0.64	0.07	-0.28	-0.58		
	det-greedy		4.61		5.18	0.76	-0.23	0.02	-0.63	0.07	-0.28	-0.58	
	det-relaxed			1.01	5.20	0.77		-0.63	0.07	-0.28	-0.58		
	our method $\alpha=0.10$				4.24	0.98		-0.04	0.00	0.00	0.00		
	our method $\alpha=0.05$				4.37	0.98		-0.09	0.01	0.00	0.00		
gender, equality-of opportunity													
bnn	det-cons		5.92		0.86			-0.64	0.08	-0.28	-0.58		
	det-greedy		5.53		5.23	0.83	-0.21	0.02	-0.63	0.07	-0.28	-0.58	
	det-relaxed			1.00	5.24	0.84		-0.63	0.07	-0.28	-0.58		
	our method $\alpha=0.10$				5.12	0.98		-0.04	0.00	0.00	0.00		
	our method $\alpha=0.05$				5.27	0.98		-0.08	0.01	0.00	0.00		
bnn-emb	det-cons		5.82		0.78			-0.64	0.07	-0.28	-0.58		
	det-greedy		4.62		5.20	0.76	-0.23	0.03	-0.63	0.07	-0.28	-0.58	
	det-relaxed			1.01	5.22	0.77		-0.63	0.07	-0.28	-0.58		
	our method $\alpha=0.10$				4.25	0.97		-0.04	0.00	0.00	0.00		
	our method $\alpha=0.05$				4.37	0.98		-0.09	0.01	0.00	0.00		

Tables 14, 10 and 12 reveal popularity bias across different domains and baselines. The ndkl metric, where 0 represents the ideal value indicating perfect alignment with the desired distribution, consistently showed substantial positive values across all baselines. Specifically, we observed ndkl values ranging from 102.01 to 110.31 for dblp, 61.74 to 74.67 for imdb, and 42.11 to 110.13 for uspt datasets, indicating divergence from the desired distribution obtained by demographic parity and equality-of opportunity fairness notions. This deviation demonstrates that the baselines disproportionately favored popular experts, effectively marginalizing less frequently occurring experts in the recommended teams. The consistency of the observed pattern indicates that popularity bias is not confined to any single domain but rather represents a systematic issue in neural team recommendation baselines before our fairness interventions.

The skew metric, which is symmetric around 0, representing the desired representation, provides a more detailed view of representation disparities. Positive values indicate over-representation and negative values signal under-representation of protected

TABLE 9 Average performance of 5-fold neural models on test set on `imdb` dataset. For the metrics, `ndkl`, the lower the better (\downarrow), `skew`, the closer to 0 the better ($\rightarrow 0$), and `map` and `ndcg`, the higher the better (\uparrow).

		%ndkl before	%ndkl after	skew before $\rightarrow 0$		skew after $\rightarrow 0$		%map10	%ndcg10
		\downarrow	\downarrow	nonprotected	protected	nonprotected	protected	$\Delta \uparrow$	$\Delta \uparrow$
popularity, demographic parity									
bnn	det-cons	16.59				-0.54	0.26	-0.36	-0.82
	det-greedy	16.60		0.74	-4.01	-0.54	0.26	-0.36	-0.82
	det-relaxed	16.35				-0.53	0.26	-0.36	-0.82
	our method	17.27				0.21	-0.19	0.00	0.00
bnn-emb	det-cons	15.71				-0.46	0.23	-0.48	-1.03
	det-greedy	15.72		0.7870	-4.30	-0.46	0.23	-0.48	-1.03
	det-relaxed	15.43				-0.45	0.23	-0.48	-1.03
	our method	17.53				0.21	-0.19	0.00	0.00
popularity, equality of opportunity									
bnn	det-cons	19.85				-0.62	0.32	-0.35	-0.81
	det-greedy	20.11		0.68	-3.96	-0.62	0.32	-0.35	-0.81
	det-relaxed	19.70				-0.62	0.32	-0.35	-0.81
	our method	16.61				0.19	-0.20	0.00	0.00
bnn-emb	det-cons	18.94				-0.55	0.30	-0.48	-1.03
	det-greedy	19.17		0.72	-4.17	-0.55	0.30	-0.48	-1.03
	det-relaxed	18.68				-0.55	0.30	-0.48	-1.03
	our method	18.15				0.20	-0.20	0.00	0.00
gender, demographic parity									
bnn	det-cons	4.44				0.03	-0.34	-0.36	-0.81
	det-greedy	3.96		0.00	-0.04	0.04	-0.36	-0.36	-0.81
	det-relaxed	4.00				0.04	-0.35	-0.36	-0.81
	our method	4.09				0.00	-0.04	0.00	0.00
bnn-emb	det-cons	8.34				0.06	-0.61	-1.17	-1.03
	det-greedy	3.99		0.01	-0.13	0.03	-0.33	-1.17	-1.03
	det-relaxed	4.21				0.03	-0.31	-1.17	-1.03
	our method	4.88				0.01	-0.12	0.00	0.00
gender, equality of opportunity									
bnn	det-cons	3.97				0.03	-0.27	-0.42	-0.99
	det-greedy	3.67		0.00	-0.06	0.03	-0.25	-0.42	-0.99
	det-relaxed	3.71				0.02	-0.25	-0.42	-0.99
	our method	3.39				0.00	-0.05	0.00	0.00
bnn-emb	det-cons	4.17				0.02	-0.24	-0.54	-1.20
	det-greedy	3.89		0.01	-0.13	0.02	-0.22	-0.54	-1.20
	det-relaxed	3.93				0.02	-0.21	-0.54	-1.20
	our method	3.96				0.01	-0.13	0.00	0.00

groups. This metric also shows consistent patterns of popularity bias across our experimental settings. Tables 14, 10 and 12 demonstrate that across all domains and baselines before our fairness considerations, there is a systematic over-representation of popular experts (indicated by positive `skew` values) joint with consistent under-representation of nonpopular experts (negative `skew`). This bidirectional deviation from the ideal case is particularly informative as it quantifies not just the presence of popularity bias, but its direction and magnitude. For instance, in the `dblp` dataset, with demographic parity notion of fairness and bnn team recommendation baseline, popular experts showed a `skew` of 1.13, indicating they received more recommendations than would be expected based on their proportion in the entire dataset. Conversely, nonpopular experts exhibited a `skew` of -19.97, suggesting they were recommended less frequently than desired. Similar patterns emerged in both the `imdb` and `uspt` datasets, with popular experts consistently showing positive values and nonpopular experts showing negative values.

Finding 1. Neural team recommendation baselines, regardless of the underlying architecture, withhold substantial biases in both popularity and gender representation before our debiasing intervention.

In response to **RQ1**, whether our proposed probabilistic reranking method can mitigate popularity bias in the recommended team of experts based on demographic parity and **equality of opportunity** while maintaining the team's likelihood of success, from Tables 14, 10 and 12, we can observe that our method could substantially reduce the bias of the neural team recommendation baselines in terms of `ndkl` and `skew` (closer to 0) with no change to the information retrieval metrics on all datasets. With respect to gender bias, however, our reranking method falls short; `ndkl` and `skew` values after applying our reranking methods

TABLE 10 Average performance of 5-fold neural models on test set on `imdb` dataset. For the metrics, `ndkl`, the lower the better (\downarrow), `expo`, the closer to 1 the better ($\rightarrow 1$), `skew`, the closer to 0 the better ($\rightarrow 0$), and `map` and `ndcg`, the higher the better (\uparrow).

<code>imdb</code>	%ndkl \downarrow		expo $\rightarrow 1$		skew before $\rightarrow 0$				skew after $\rightarrow 0$		%map10	%ndcg10
			before	after	before	after	protected disadvantaged	nonprotected advantaged	protected disadvantaged	nonprotected advantaged	$\Delta \uparrow$	$\Delta \uparrow$
		before	after									
popularity, demographic parity												
bnn	det-cons		16.59			0			0.26	-0.54	-0.36	-0.82
	det-greedy		16.60			0			0.26	-0.54	-0.36	-0.82
	det-relaxed	67.53		0	0	-4.01	0.74		0.26	-0.53	-0.36	-0.82
	our method $\alpha=0.10$		17.27			0			-0.19	0.21	0.00	0.00
	our method $\alpha=0.05$		20.16			0			-0.21	0.23	0.00	0.00
bnn-emb	det-cons		15.71			0			0.23	-0.46	-0.48	-1.03
	det-greedy		15.72			0			0.23	-0.46	-0.48	-1.03
	det-relaxed	74.67		0	0	-4.30	0.7870		0.23	-0.45	-0.48	-1.03
	our method $\alpha=0.10$		17.53			0			-0.19	0.21	0.00	0.00
	our method $\alpha=0.05$		20.52			0			-0.21	0.23	0.00	0.00
popularity, equality of opportunity												
bnn	det-cons		19.85			0			0.32	-0.62	-0.35	-0.81
	det-greedy		20.11			0			0.32	-0.62	-0.35	-0.81
	det-relaxed	61.74		0	0	-3.96	0.68		0.32	-0.62	-0.35	-0.81
	our method $\alpha=0.10$		16.61			0			-0.20	0.19	0.00	0.00
	our method $\alpha=0.05$		19.29			0			-0.24	0.22	0.00	0.00
bnn-emb	det-cons		18.94			0			0.30	-0.55	-0.48	-1.03
	det-greedy		19.17			0			0.30	-0.55	-0.48	-1.03
	det-relaxed	68.57		0	0	-4.24	0.71		0.30	-0.55	-0.48	-1.03
	our method $\alpha=0.10$		18.15			0			-0.20	0.20	0.00	0.00
	our method $\alpha=0.05$		19.66			0			-0.24	0.22	0.00	0.00
gender, demographic parity												
bnn	det-cons		4.44			0			-0.34	0.03	-0.36	-0.81
	det-greedy		3.96			0			-0.36	0.04	-0.36	-0.81
	det-relaxed	4.13		0	0	-0.04	0.00		-0.35	0.04	-0.36	-0.81
	our method $\alpha=0.10$		4.09			0			-0.04	0.00	0.00	0.00
	our method $\alpha=0.05$		3.89			0			0.06	-0.01	0.00	0.00
bnn-emb	det-cons		8.34			0			-0.61	0.06	-1.17	-1.03
	det-greedy		3.99			0			-0.33	0.03	-1.17	-1.03
	det-relaxed	4.92		0	0	-0.13	0.01		-0.31	0.03	-1.17	-1.03
	our method $\alpha=0.10$		4.88			0			-0.12	0.01	0.00	0.00
	our method $\alpha=0.05$		4.53			0			0.01	0.00	0.00	0.00
gender, equality of opportunity												
bnn	det-cons		3.97			0			-0.27	0.03	-0.42	-0.99
	det-greedy		3.67			0			-0.25	0.03	-0.42	-0.99
	det-relaxed	3.42		0	0	-0.06	0.00		-0.25	0.02	-0.42	-0.99
	our method $\alpha=0.10$		3.39			0			-0.05	0.00	0.00	0.00
	our method $\alpha=0.05$		3.41			0			-0.06	0.00	0.00	0.00
bnn-emb	det-cons		4.17			0			-0.24	0.02	-0.54	-1.20
	det-greedy		3.89			0			-0.22	0.02	-0.54	-1.20
	det-relaxed	4.84		0	0	-0.05	0.00		-0.21	0.02	-0.54	-1.20
	our method $\alpha=0.10$		3.96			0			-0.13	0.01	0.00	0.00
	our method $\alpha=0.05$		4.51			0			0.09	-0.01	0.00	0.00

733 generally remain the same, or become worse (larger value) in several settings like for bnn baseline on `uspt` dataset where
734 `ndkl` has increased from 6.50 to 11.46 after applying our method. We attribute this to the extreme gender bias in datasets (e.g.,
735 0.862 to 0.138 male vs. female ratio in `uspt`) such that the original top- k ranked list lacks enough (qualified) female experts.

736 **Finding 2.** Our proposed probabilistic reranking can mitigate **popularity** bias while maintaining utility across *all* domains.

737 However, our method exhibits clear limitations when addressing gender bias. The fairness metrics, `ndkl` and `skew` values
738 post-reranking generally remain the same or become worse. For instance, applying our method to the bnn baseline on the
739 `uspt` dataset resulted in a significant degradation, with `ndkl` increasing from 6.50 to 11.46. This limitation stems from severe

TABLE 11 Average performance of 5-fold neural models on test set on uspt dataset. For the metrics, `ndkl`, the lower the better (\downarrow), `skew`, the closer to 0 the better ($\rightarrow 0$), and `map` and `ndcg`, the higher the better (\downarrow).

		%ndkl before \downarrow	%ndkl after \downarrow	skew before $\rightarrow 0$ protected	skew before $\rightarrow 0$ nonprotected	skew after $\rightarrow 0$ protected	skew after $\rightarrow 0$ nonprotected	%map@10 $\Delta \uparrow$	%ndcg@10 $\Delta \uparrow$
popularity, demographic parity									
bnn	det-cons	24.36				0.81	0.78	-0.24	-0.53
	det-greedy	90.93	24.35	-10.58	1.05	0.81	0.78	-0.24	-0.53
	det-relaxed		28.94			-0.80	0.78	-0.24	-0.53
	our method		18.52			-0.13	0.59	0.00	0.00
bnn-emb	det-cons		18.88			-0.61	0.68	-0.67	-1.35
	det-greedy	110.13	18.88	-22.79	1.13	-0.61	0.68	-0.67	-1.35
	det-relaxed		24.13			-0.60	0.67	-0.67	-1.35
	our method		19.68			-0.15	0.22	0.00	0.00
popularity, equality of opportunity									
bnn	det-cons		16.12			-0.32	0.24	-0.24	-0.53
	det-greedy	42.11	20.39	-9.95	0.44	-0.32	0.24	-0.24	-0.53
	det-relaxed		19.06			-0.32	0.24	-0.24	-0.53
	our method		17.20			-0.14	-0.62	0.00	0.00
bnn-emb	det-cons		14.50			-0.18	0.18	-0.67	-1.35
	det-greedy	52.44	19.48	-22.16	0.53	-0.18	0.18	-0.67	-1.35
	det-relaxed		18.04			-0.18	0.18	-0.67	-1.35
	our method		14.65			-0.21	0.13	0.00	0.00
gender, demographic parity									
bnn	det-cons		3.73			0.13	-0.02	-0.24	-0.53
	det-greedy	6.50	2.67	0.30	-0.08	0.13	-0.02	-0.24	-0.53
	det-relaxed		3.51			0.13	-0.25	-0.24	-0.53
	our method		11.46			0.36	-0.37	0.00	0.00
bnn-emb	det-cons		4.52			0.13	-0.02	-0.67	-1.35
	det-greedy	8.07	2.68	0.54	-0.13	0.13	-0.02	-0.67	-1.35
	det-relaxed		4.37			0.12	-0.02	-0.67	-1.35
	our method		8.32			0.55	-0.141	0.00	0.00
gender, equality of opportunity									
bnn	det-cons		10.15			0.00	0.07	-0.24	-0.53
	det-greedy	12.08	9.03	0.20	0.00	0.00	0.07	-0.24	-0.53
	det-relaxed		9.71			0.00	0.07	-0.24	-0.53
	our method		16.40			0.33	-0.33	0.00	0.00
bnn-emb	det-cons		10.81			0.01	0.06	-0.67	-1.35
	det-greedy	12.80	9.15	0.44	-0.04	0.01	0.06	-0.67	-1.35
	det-relaxed		10.49			0.01	0.06	-0.67	-1.35
	our method		12.8			0.47	-0.05	0.00	0.00

740 pre-existing biases in the underlying data distributions, exemplified by the severe gender imbalance in datasets such as uspt
741 with its 0.862 to 0.138 male-to-female ratio. Such extreme gender bias creates a fundamental limitation where the top- k ranked
742 lists of experts simply lack a sufficient pool of qualified female experts to draw from. Additionally, our results point to the
743 broader challenge of achieving fairness in domains with extreme under-representation, where the space of possible fair solutions
744 is constrained by the available expert pool.

Finding 3. Different types of bias may require distinct mitigation strategies due to the *level* of bias across different protected attributes.

745 To answer **RQ2**, regarding whether our proposed probabilistic reranking method outperforms deterministic reranking methods,
746 from Tables 14, 10 and 12 we observe that our probabilistic method demonstrates superior performance over deterministic
747 rerankers specifically in mitigating popularity bias across various fairness notions on all datasets, as evidenced by the combination
748 of fairness and information retrieval metrics. This superiority is reflected in the consistency of bias reduction and maintaining
749 information retrieval metrics. While deterministic rerankers show some capability in mitigating popularity bias, this comes at the
750 cost of a drastic drop in information retrieval metrics. Specifically, we observe consistent negative values in $\Delta_{\text{map}}@10$ and
751 $\Delta_{\text{ndcg}}@10$, indicating drops in recommendation quality. This trade-off between fairness and accuracy highlights an important
752 advantage of our probabilistic approach, which maintains recommendation quality while improving fairness metrics.
753

TABLE 12 Average performance of 5-fold neural models on test set on uspt dataset. For the metrics, `ndkl`, the lower the better (\downarrow), `expo`, the closer to 1 the better ($\rightarrow 1$), `skew`, the closer to 0 the better ($\rightarrow 0$), and `map` and `ndcg`, the higher the better (\uparrow).

uspt		%ndkl \downarrow		expo $\rightarrow 1$		skew before $\rightarrow 0$		skew after $\rightarrow 0$		%map \uparrow	%ndcg \uparrow
		before	after	before	after	protected disadvantaged	nonprotected advantaged	protected disadvantaged	nonprotected advantaged	$\Delta \uparrow$	$\Delta \uparrow$
popularity, demographic parity											
bnn	det-cons		24.36		1.23			0.81	0.78	-0.24	-0.53
	det-greedy		24.35		1.23		-10.58	1.05	0.81	0.78	-0.24
	det-relaxed	90.93		0.67	1.12			-0.80	0.78	-0.24	-0.53
	our method $\alpha=0.10$		18.52		0.98			-0.13	-0.59	0.00	0.00
	our method $\alpha=0.05$		21.73		0.96			-0.14	-0.57	0.00	0.00
bnn-emb	det-cons		18.88		1.13			-0.61	0.68	-0.67	-1.35
	det-greedy		18.88		1.13		-22.79	1.13	-0.61	0.68	-0.67
	det-relaxed	110.13		0.15	1.02			-0.60	0.67	-0.67	-1.35
	our method $\alpha=0.10$		19.68		1.05			-0.15	0.22	0.00	0.00
	our method $\alpha=0.05$		23.63		1.02			-0.16	0.24	0.00	0.00
popularity, equality-of opportunity											
bnn	det-cons		16.12		1.32			-0.32	0.24	-0.24	-0.53
	det-greedy		20.39		1.42		-9.95	0.44	-0.32	0.24	-0.24
	det-relaxed	42.11		0.67	1.38			-0.32	0.24	-0.24	-0.53
	our method $\alpha=0.10$		17.20		0.99			-0.14	-0.62	0.00	0.00
	our method $\alpha=0.05$		18.67		0.97			-0.18	-0.58	0.00	0.00
bnn-emb	det-cons		14.50		1.22			-0.18	0.18	-0.67	-1.35
	det-greedy		19.48		1.32		-22.16	0.53	-0.18	0.18	-0.67
	det-relaxed	52.44		0.15	1.28			-0.18	0.18	-0.67	-1.35
	our method $\alpha=0.10$		18.04		1.04			-0.21	0.13	0.00	0.00
	our method $\alpha=0.05$		14.65		1.02			-0.26	0.15	0.00	0.00
gender, demographic parity											
bnn	det-cons		3.73		0.99			0.13	-0.02	-0.24	-0.53
	det-greedy		2.67		1.00			0.13	-0.02	-0.24	-0.53
	det-relaxed	6.50		0.94	0.94	0.30	-0.08	0.13	-0.25	-0.24	-0.53
	our method $\alpha=0.10$		3.51		0.98			0.36	-0.37	0.00	0.00
	our method $\alpha=0.05$		11.46		0.97			0.35	-0.32	0.00	0.00
bnn-emb	det-cons		4.52		1.01			0.13	-0.02	-0.67	-1.35
	det-greedy		2.68		1.00			0.13	-0.02	-0.67	-1.35
	det-relaxed	8.07		0.97	1.01	0.54	-0.13	0.12	-0.02	-0.67	-1.35
	our method $\alpha=0.10$		4.37		0.99			0.55	-0.14	0.00	0.00
	our method $\alpha=0.05$		8.32		0.97			0.55	-0.13	0.00	0.00
gender, equality-of opportunity											
bnn	det-cons		10.10		1.00			0.00	0.07	-0.24	-0.53
	det-greedy		9.03		1.01			0.00	0.07	-0.24	-0.53
	det-relaxed	12.08		0.94	1.01	0.20	0.00	0.00	0.07	-0.24	-0.53
	our method $\alpha=0.10$		9.71		0.97			0.33	-0.33	0.00	0.00
	our method $\alpha=0.05$		16.40		0.97			0.31	-0.30	0.00	0.00
bnn-emb	det-cons		10.81		1.02			0.01	0.06	-0.67	-1.35
	det-greedy		9.15		1.00			0.01	0.06	-0.67	-1.35
	det-relaxed	12.80		0.97	1.01	0.44	-0.04	0.01	0.06	-0.67	-1.35
	our method $\alpha=0.10$		10.49		0.97			0.47	-0.05	0.00	0.00
	our method $\alpha=0.05$		12.80		0.97			0.46	-0.05	0.00	0.00

754 The effectiveness of gender bias mitigation strategies demonstrates fewer clear-cut results. Deterministic rerankers achieve
 755 marginally better fairness metrics, showing improvements in `ndkl` and `skew` values, compared to our probabilistic method.
 756 However, this modest improvement in fairness comes at a considerable cost to recommendation accuracy, with deterministic
 757 approaches showing a significant loss in information retrieval metrics. This suggests that while deterministic approaches might
 758 achieve slightly better results in terms of mitigating gender bias, they sacrifice substantial recommendation quality, questioning
 759 their practical applicability.

760 It is particularly noteworthy that all deterministic rerankers exhibit similar performance patterns across datasets, with no
 761 single approach demonstrating clear dominance over the others. This finding aligns with Loghmani et al.'s³⁵ observations and
 762 suggests a fundamental limitation in deterministic approaches. While deterministic approaches might seem appealing due to

763 their simplicity and interpretability, our findings suggest that probabilistic methods offer a better approach to addressing bias,
 764 considering both fairness and accuracy.

Finding 4. In the context of neural team recommendation, our proposed probabilistic reranking method consistently outperforms deterministic reranking methods on all datasets and baselines.

765
 766 For **RQ3**, regarding the analysis of expo metric where the ideal value is 1, indicating that the protected groups' exposure is
 767 perfectly proportional to their utility scores, and values less (greater) than 1 suggest bias against (in favor of) the disadvantaged
 768 group, from Table 14, 10 and 12, we observe that our proposed probabilistic reranking method shows improvements for
 769 protected groups across datasets, particularly for popularity as the protected attribute. For nonpopular items, we observe
 770 consistent and substantial improvements across all datasets. Before reranking, the baseline bnn exhibited significant bias against
 771 nonpopular groups, with expo values substantially less than 1 across all datasets. After applying our probabilistic reranking
 772 method, these values were adjusted closer to the ideal. This shift indicates that our method effectively balanced the exposure
 773 of nonpopular groups relative to their success, mitigating the initial bias. In contrast, deterministic reranking algorithms often
 774 overcompensated, resulting in expo values significantly greater than 1. For instance, det-cons produced values of 2.436 for
 775 dblp on bnn baseline with demographic parity. These elevated values suggest reverse discrimination, favouring the
 776 disadvantaged group disproportionately.

777 With respect to gender, the results are, however, relatively poor, similar to **RQ2** and ~~Tables 14, 10 and 12~~. All post-processing
 778 reranking methods fall short of mitigating the gender bias, which can be attributed to the presence of extreme gender bias in the
 779 dataset. For instance, with male-to-female ratios as skewed as 0.862 to 0.138 in uspt, the top- k ranked list of experts lacks
 780 sufficient representation of female experts, making it impossible for post-processing methods alone to achieve fairness without
 781 compromising quality. Nonetheless, although our proposed probabilistic method negligibly changes the values of expo for
 782 better or worse across different settings, its performance is better than deterministic reranking methods. This is evidenced by
 783 how deterministic methods tend to push expo values well above 1, indicating an artificial inflation of female representation that
 784 compromises the quality of recommendations.

785 In summary, our probabilistic reranking method consistently mitigated popularity bias across all datasets and fairness
 786 definitions while maintaining utility in terms of expo . Unlike deterministic methods that may overcompensate and drop utility
 787 drastically, our approach presents a balance by proportionally adjusting exposure based on information retrieval metrics. Also,
 788 our method successfully improves the ratio of exposure to utility for disadvantaged groups, moving expo values towards the
 789 ideal 1 across multiple datasets and fairness definitions.

Finding 5. Our probabilistic reranking method's performance in terms of expo is consistent with its fairness metrics
 790 namely ndkl and skew across all settings and domains.

791 Regarding **RQ4**, Tables 14, 10 and 12 demonstrate that each fairness-aware reranker, whether deterministic or probabilistic,
 792 follows a similar trend across the dblp, imbd, and uspt datasets, despite these datasets originating from different domains.
 793 Specifically, the performance metrics, including fairness measures and utility metrics, remain consistent in terms of their trends
 794 when applying the same reranking algorithms to different datasets. This consistency suggests that the inherent patterns of bias
 795 and the distribution of protected attributes are similar across these datasets, as illustrated in Figure 2. Moreover, the similarity in
 796 trends indicates that the fairness-aware reranking algorithms are robust to domain variations and can generalize well across
 797 different domains. This robustness also implies that the underlying biases in rankings are not unique to a particular domain
 798 but are pervasive across various domains. Consequently, fairness interventions that are effective in one domain are likely to be
 799 effective in others.

Finding 6. Our proposed probabilistic reranking method shows consistent effective performance in terms of both fairness
 800 and information retrieval metrics across datasets from different domains.

801 Lastly, our experiments show that while post-processing reranking methods can effectively address biases, their efficacy
 802 may become limited when employed single-handedly when confronting *extreme* biases in a dataset; such methods struggle to
 803 rectify biases without a consequential loss in accuracy. A holistic approach that integrates pre-processing, in-processing, and
 804 post-processing methods is required to achieve a more balanced and optimal outcome.

TABLE 13 Average performance of 5-fold neural models in terms of expo on test set on `imdb`, `dblp`, `uspt` datasets. For this metric expo , the closer to 1 the better ($\rightarrow 1$)

		imdb		dblp		uspt	
		$\text{expo} \rightarrow 1$		$\text{expo} \rightarrow 1$		$\text{expo} \rightarrow 1$	
		before	after	before	after	before	after
popularity, demographic parity							
bnn	det-cons		1.7014		2.4358		1.2303
	det-greedy	0.7737	1.7014	0.2612	2.7576	0.6774	1.2314
	det-relaxed		1.6491		2.2494		1.1268
	our method		1.0053		1.0122		0.9858
bnn-emb	det-cons		1.6838		2.5549		1.1328
	det-greedy	0.7705	1.6838	0.2382	2.5552	0.1564	1.1327
	det-relaxed		1.6320		2.3588		1.0296
	our method		0.9887		1.0316		1.0544
popularity, equality of opportunity							
bnn	det-cons		1.6836		2.4456		1.3286
	det-greedy	0.7737	1.6951	0.2612	2.4488	0.6774	1.4296
	det-relaxed		1.6434		2.2681		1.3889
	our method		0.8406		1.0139		0.9909
bnn-emb	det-cons		1.6677		2.5813		1.2239
	det-greedy	0.7705	1.6795	0.2382	2.5839	0.1564	1.3298
	det-relaxed		1.6261		2.3951		1.2892
	our method		0.8377		1.0338		1.0415
gender, demographic parity							
bnn	det-cons		1.1357		1.1106		0.9925
	det-greedy	0.9195	1.1640	0.9741	1.1024	0.9461	1.0002
	det-relaxed		1.1610		1.1433		0.9481
	our method		0.9066		0.9750		0.9814
bnn-emb	det-cons		1.3136		1.1528		1.0175
	det-greedy	0.9302	1.3003	1.0084	1.1540	0.9761	1.0011
	det-relaxed		1.3082		1.1693		1.0128
	our method		0.9233		1.0080		0.9779
gender, equality of opportunity							
bnn	det-cons		1.1314		1.1324		1.0065
	det-greedy	0.9195	1.1563	0.9741	1.1242	0.9461	1.0144
	det-relaxed		1.1561		1.1597		1.0189
	our method		0.9066		0.9743		0.9784
bnn-emb	det-cons		1.2875		1.1728		1.0228
	det-greedy	0.9302	1.2909	1.0084	1.1742	0.9761	1.0047
	det-relaxed		1.2971		1.2047		1.0191
	our method		0.9233		1.0014		0.9752

5 | CONCLUDING REMARKS

In this paper, we formalized the fair team recommendation problem, where we aim to form an unbiased collaborative group of diverse experts to accomplish complex tasks. While state-of-the-art neural team recommenders can efficiently recommend sets of candidate experts to form effective collaborative teams, they are largely biased toward *male* and *popular* experts, potentially overlooking valuable contributors from under-represented groups. We proposed a model-agnostic post-processing probabilistic reranking method to mitigate unfair biases in the recommended teams of experts by neural team recommendation models, focusing on maintaining team effectiveness while promoting fairness with respect to demographic parity and *equality of opportunity* notions of fairness. Our experiments on three large-scale benchmark datasets from different domains, including `imdb`, `dblp`, and `uspt`, showed that: (1) neural team recommenders heavily suffer from biases toward popular and male experts, with popular experts; (2) probabilistic greedy reranking algorithms can substantially mitigate popularity biases while maintaining models' efficacy; (3) Biases appeared across all neural team recommendation architectures, indicating it is a fundamental challenge of these systems rather than a flaw in specific model designs; (4) In the presence of extreme biases, where initial recommendations show more than 80% skew toward certain groups, post-processing reranking methods fall short of achieving fair representation. (5) our probabilistic method dominantly outperforms deterministic baselines and is robust towards domain changes. Our future research direction includes mitigating multiple biases jointly, i.e., gender bias together with

TABLE 14 Average performance of 5-fold neural models on test set on dblp dataset. For the metrics, ndkl, the lower the better (\downarrow), expo, the closer to 1 the better ($\rightarrow 1$), skew, the closer to 0 the better ($\rightarrow 0$), and map and ndcg, the higher the better (\uparrow).

dblp	%ndkl \downarrow		expo $\rightarrow 1$		skew before $\rightarrow 0$				skew after $\rightarrow 0$		%map5	%ndcg5
	before	after	before	after	protected disadvantaged	nonprotected advantaged	protected disadvantaged	nonprotected advantaged	$\Delta \uparrow$	$\Delta \uparrow$		
popularity, demographic parity												
bnn	det-cons	14.64		2.43			-0.54	0.64	-0.23	-0.42		
	det-greedy	14.64		2.75			-0.54	0.64	-0.23	-0.42		
	det-relaxed	109.56	18.31	0.26	2.24	-19.97	1.13	-0.53	0.64	-0.23	-0.42	
	our method $\alpha=0.10$	19.71			1.01			-0.15	0.26	0.00	0.00	
	our method $\alpha=0.05$	22.25			0.99			-0.16	0.25	0.00	0.00	
bnn-emb	det-cons	14.09		2.55			-0.51	0.62	-0.23	-0.42		
	det-greedy	14.09		2.55			-0.51	0.62	-0.23	-0.42		
	det-relaxed	110.31	17.65	0.23	2.35	-20.75	1.14	-0.50	0.61	-0.23	-0.42	
	our method $\alpha=0.10$	19.61			1.03			-0.15	0.26	0.00	0.00	
	our method $\alpha=0.05$	22.16			1.01			-0.17	0.29	0.00	0.00	
popularity, equality-of opportunity												
bnn	det-cons	13.12		2.44			-0.51	0.57	-0.23	-0.42		
	det-greedy	13.16		2.44			-0.51	0.57	-0.23	-0.42		
	det-relaxed	102.01	16.15	0.26	2.26	-19.92	1.05	-0.50	0.57	-0.23	-0.42	
	our method $\alpha=0.10$	18.96			1.01			-0.16	0.24	0.00	0.00	
	our method $\alpha=0.05$	22.61			0.99			-0.18	0.27	0.00	0.00	
bnn-emb	det-cons	12.65		2.58			-0.48	0.55	-0.23	-0.42		
	det-greedy	12.67		2.58			-0.48	0.55	-0.23	-0.42		
	det-relaxed	102.85	15.63	0.23	2.39	-20.62	1.06	-0.47	0.55	-0.23	-0.42	
	our method $\alpha=0.10$	18.39			1.03			-0.16	0.25	0.00	0.00	
	our method $\alpha=0.05$	22.52			1.01			-0.18	0.28	0.00	0.00	
gender, demographic parity												
bnn	det-cons	5.90		0.86			-0.63	0.07	-0.23	-0.42		
	det-greedy	5.21		0.83			-0.63	0.07	-0.23	-0.42		
	det-relaxed	5.52	5.21	1.01	0.83	-0.20	0.02	-0.63	0.07	-0.23	-0.42	
	our method $\alpha=0.10$	5.12			0.98			-0.03	0.00	0.00	0.00	
	our method $\alpha=0.05$	5.27			0.98			-0.08	0.00	0.00	0.00	
bnn-emb	det-cons	5.80		0.78			-0.64	0.07	-0.23	-0.42		
	det-greedy	5.18		0.76			-0.63	0.07	-0.23	-0.42		
	det-relaxed	4.61	5.20	1.01	0.77	-0.23	0.02	-0.63	0.07	-0.23	-0.42	
	our method $\alpha=0.10$	4.24			0.98			-0.04	0.00	0.00	0.00	
	our method $\alpha=0.05$	4.37			0.98			-0.09	0.01	0.00	0.00	
gender, equality-of opportunity												
bnn	det-cons	5.92		0.86			-0.64	0.08	-0.23	-0.42		
	det-greedy	5.23		0.83			-0.63	0.07	-0.23	-0.42		
	det-relaxed	5.53	5.24	1.00	0.84	-0.21	0.02	-0.63	0.07	-0.23	-0.42	
	our method $\alpha=0.10$	5.12			0.98			-0.04	0.00	0.00	0.00	
	our method $\alpha=0.05$	5.27			0.98			-0.08	0.01	0.00	0.00	
bnn-emb	det-cons	5.82		0.78			-0.64	0.07	-0.23	-0.42		
	det-greedy	5.20		0.76			-0.63	0.07	-0.23	-0.42		
	det-relaxed	4.62	5.22	1.01	0.77	-0.23	0.03	-0.63	0.07	-0.23	-0.42	
	our method $\alpha=0.10$	4.25			0.97			-0.04	0.00	0.00	0.00	
	our method $\alpha=0.05$	4.37			0.98			-0.09	0.01	0.00	0.00	

820 popularity bias, and incorporating in-processing methods to address these challenges at the model training stage rather than
821 solely through post-processing adjustments.

822 6 | ETHICAL CONSIDERATIONS

823 We utilized genderize to obtain missing genders for individuals in the imdb and all of the experts in the dblp dataset. Gen-
824 derize is a crowd-based system that predicts a gender for a given name with a probability based on the number of appearan-
825 ces of a name in their database, name patterns and cultural associations, which may be reasonably accurate, it inherently incorpo-
826 rates societal biases and assumptions that can be problematic.

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