

CAREER: Behavior-Informed Machine Learning: Improving Robust Learning and Decision Support

1 Introduction

Machine learning (ML) is increasingly integrating into various aspects of everyday human life, making it more crucial than ever to consider the roles of humans in the design of ML systems. Existing approaches in ML often either treat humans as independent, stochastic data sources [23, 135, 104, 141] or assume humans are *rational* decision-makers [131, 19, 18, 45, 66, 7]. While these assumptions allow for elegant and simple formulations, they deviate from actual human behavior, as extensively documented in the psychology literature [127, 60, 129, 59, 63, 61]. Failure to properly account for human behavior in the design of ML systems can lead to unintended negative consequences. A notable example is Microsoft’s chatbot Tay in 2016. Tay was designed to learn from conversations with Twitter users, but it had to be deactivated within 16 hours due to its unanticipated adoption of offensive language, a direct consequence of neglecting to account for the behaviors of human users [79, 136]. Similarly, ML models trained on data generated by doctor annotations might recommend unnecessary treatments due to doctors’ action bias towards treating diseases, even when the best course of action might be to wait and observe [33, 90, 124]. ML models on social media platforms that recommend content to users can inadvertently create echo chambers due to the confirmation bias in user behavior [92, 96, 11]. Autonomous vehicles designed by learning from human driving behavior could adopt dangerous patterns from aggressive or unsafe drivers [26]. These examples highlight the urgent need to consider human behavior when designing ML systems.

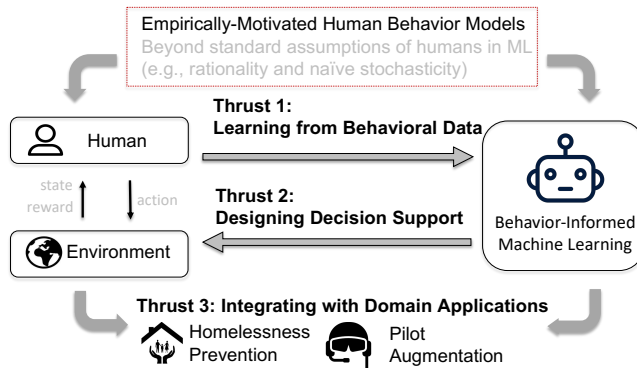


Figure 1: CAREER research plan. [CJ: to fine-tune]

This CAREER project proposes the development of a framework for *behavior-informed machine learning*, which examines and incorporates the impacts of human behavior into the design of machine learning systems. Specifically, I will focus on two key aspects of human behavior in the ML lifecycle: (1) The generation of data used for training machine learning models, and (2) human decision-making in tandem with machine assistance. The proposed research aims to devise ML systems resilient to biased training data, and capable of enhancing human decision-making for improved outcomes. In addition to theoretical con-

tributions, through collaboration with domain experts, the research will be adapted to domain applications such as homelessness prevention and pilot augmentation. This ensures that the research findings will have practical relevance in domain applications, promoting their widespread adoption and impact. In more detail, as illustrated in Figure 1, I will investigate the following three research thrusts:

- **Thrust 1: Developing foundations for learning from human behavioral data.**

Learning from human supervisions and demonstrations has been extensively studied in weakly supervised learning [14, 86, 109], truth inference in crowdsourcing [104, 22, 135, 23, 141], and inverse reinforcement learning [87, 142, 100]. In these studies, humans are mostly assumed to be either rational or naively stochastic, deviating from actual human behavior. This thrust aims to develop computationally practical, theoretically sound, and empirically grounded foundations for learning from behavioral data, explicitly accounting for empirically-supported human behavior in data generation.

- **Thrust 2: Designing assistive ML to improve human decision making.**

As ML begins to outperform humans in certain areas, it is becoming more important than ever to explore

how ML can be leveraged to assist humans in making better decisions. In this thrust, I aim to develop assistive ML frameworks to enhance human decision making that take into account human behavior. I will investigate when and what assistance ML should provide through algorithmic, data-driven, and learning approaches. Furthermore, I will conduct behavioral experiments to understand human trust and reliance on ML that will in turn impact our design of the assistive ML framework.

- **Thrust 3: Integrating with domain applications.**

While the main focus of this CAREER plan is to develop a general framework for behavior-informed ML, I will also collaborate with domain experts to tackle practical challenges in deploying this framework in domain applications. Specifically, the proposed research will be adapted for use in the domains of homelessness prevention (in collaboration with Prof. Patrick Fowler) and flight pilot augmentation (in collaboration with Boeing). This approach ensures that our research findings are robust and practically applicable in domain applications, promoting their widespread adoption and potential for impact.

Long-term Goal. My career goal is to develop the foundations for humans and ML to collaborate together and solve problems neither can solve alone. This requires the advancements of ML, the understanding of humans, and the utilization of their interactions. This research proposal serves as a stepping stone to achieving this goal by designing learning algorithms that are robust to human behavior during data generation, and investigating the design of assistive ML to augment humans in making better decisions.

Intellectual Merit. This proposal will make intellectual contributions in the following aspects. First, it contributes to empirical understanding of human behavior when interacting with ML. It also provides theoretical foundations for studying the human-machine interactions through incorporate empirically-motivated human models in the design of ML. Moreover, the proposal initiates a framework to incorporate generative AI in the learning framework. This research is interdisciplinary in nature, combining ideas and techniques from machine learning, algorithmic economics, and online behavioral social science.

PI Qualifications. The PI has extensive research experience in studying the interactions between humans and ML, using techniques drawn from ML, algorithmic economics, optimization, and online behavioral social science. From the perspective of learning from humans, the PI has explored the problem of eliciting and learning from noisy human-generated data [46, 49, 5, 53, 47, 120, 118, 29, 30] and designing incentives to encourage high-quality data [48, 50, 54, 76]. From the perspective of designing ML to assist humans, the PI's recent works explored the design of when and what assistance to provide to humans using techniques from information design and environment design [138, 119, 37, 25]. The PI also investigated ethical considerations in leveraging ML in decision making [121, 122, 84, 85]. Beyond theoretical and algorithmic studies, the PI has experiences in conducting large-scale online behavioral experiments to understand human behavior in computational environments [51, 120, 29, 30, 122, 138, 84, 85]. The PI's involvement extends into the broader research community. The PI served as the Doctoral Consortium Co-Chair and Works-in-Progress and Demonstration Co-Chair of HCOMP (in 2022 and 2019, respectively), the premier conference in the study of human computation. The PI has also organized workshops at NeurIPS and HCOMP to explore the interactions between humans and machine learning, and served as the area chair, senior program committee, and program committee in major AI/ML conferences.

2 Background

This proposal aims to integrate realistic human decision-making processes into the design of machine learning systems. While the proposed methodologies apply more broadly, the primary focus is in the context of sequential decision making in this proposal. As a groundwork for this discussion, we start with a concise introduction to the classical decision-making framework, the Markov decision process (MDP), along with associated ML frameworks. Subsequently, we provide a summary of widely recognized human behavioral models, drawing upon insights from behavioral economics and psychology.

2.1 Decision Making Framework in Machine Learning

We first review Markov decision process (MDP), the classical sequential decision-making framework that serves as the foundation of the proposed research.

Markov decision process (MDP). Markov decision process (MDP) is one of the most standard frameworks for modeling the sequential decision-making environment in ML. An MDP can be characterized by the tuple $\langle S, A, T, R \rangle$, where

- State space S : characterizes the environment a sequential decision maker is interacting with.
- Action space A : actions the decision maker can chose from at each step.
- State transition function $T(s'|s, a)$: characterizes how decision maker's actions change the environment.
- Reward function $R_a(s, s')$: describes the benefits of taking each action.

Reinforcement learning (RL). The standard approach to solve the above MDP and obtain an optimal policy is through reinforcement learning (RL) [57, 117, 81, 82]. The RL agent interacts with an unknown environment and attempts to maximize the total of its collected reward. At each time t , the agent in state $s_t \in S$ takes an action $a_t \in A$, which returns a reward $R_{a_t}(s_t, s_{t+1})$, and leads to the next state $s_{t+1} \in S$ according to $T(s'|s, a)$, the probability to state s' from s after taking action a . The goal of RL is to learn a policy $\pi(a|s)$ that maximizes the total time-discounted rewards $\mathbb{E}_\pi[\sum_t \gamma^t R_{a_t}(s_t, s_{t+1}) | \pi]$, where $\gamma \in (0, 1]$ is a discount factor ($\gamma = 1$ indicates an undiscounted MDP). RL has a long history of development, from the seminal Q-learning [133], to more recent deep learning aided approaches [74, 81, 82].

Inverse reinforcement learning (IRL). Inverse reinforcement learning tackles the problem of inferring the reward R from observing the sequence of (s_t, a_t) , assuming the observed actions are taken by *rational* decision makers. This problem has also been referred to as apprenticeship learning, or learning by watching, imitation learning etc. Ng et al. [87] is among the first to formalize this problem. The high-level idea is to find a feasible function $R(\cdot)$ such that a_t is the action maximizes the utility at s_t for all (s_t, a_t) pairs, and impose smoothness constraints on each step's predicted policy to formulate a linear programming problem. Follow-up works [4, 142, 100] have focused on variants of the optimization formulation. The common assumption in IRL is that the demonstrations (s_t, a_t) are from unbiased and optimal decision makers.

2.2 Empirically Motivated Human Behavioral Models

While existing approaches to incorporating humans in ML often either treat humans as stochastic data sources or assume humans are *rational* decision-makers, they do not always capture human behavior empirically observed in the field. In this CAREER plan, we aim to incorporate empirically grounded human models into the design of ML. While the proposed research is applicable to general human models (including data-driven forms), to make the discussion more concrete, we summarize and provide formulations of some notable classes of human behavioral models in the literature of economics and psychology.

Biased reward evaluation. While it is commonly assumed that humans are rational, taking actions to maximize their expected utility (the expected utility theory [131]), humans are consistent observed to deviate from the assumption. For example, humans often over-estimate small probabilities and react more strongly to losses than gains. The most important theory that summarizes these systematic biases is the Nobel-winning *prospect theory* [58]. Another commonly used theory, also Nobel-winning, is the discrete choice model [80, 113, 125], accounting for the inherent randomness of human decision making by incorporating noises in the utility. These deviations from standard rational assumption can often be captured with humans' biased reward evaluations. Formally, let $(p_1, x_1, \dots, p_K, x_K)$ be the *prospect* of an action, where p_k represents the probability of the outcome x_k happens after taking the action. Let $v(x_k)$ represent the utility of the outcome x_k . The above theories can be summarized below:

- Expected utility theory: It predicts that humans will take the action that maximizes $\sum_{k=1}^K p_k v(x_k)$.

- Prospect theory: It predicts that humans will take the action that maximizes $\sum_{k=1}^K \pi(p_k)u(v(x_k))$, where $\pi(\cdot)$ and $u(\cdot)$ models the humans’ distorted interpretations on the probability and utility measure.
- Discrete choice model: It predicts that humans will take the action that maximizes $\sum_{k=1}^K p_k v(x_k) + \epsilon$, where ϵ is the additional noise term that incorporates the intrinsic randomness of human decision making.

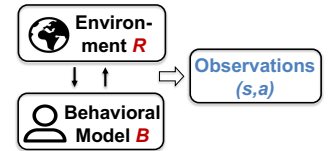
Selected information processing. Humans tend to prioritize certain types of information while neglecting others, leading to decision biases. For example, confirmation bias [88, 65] describes humans’ tendency to prioritize information agreeing with their existing beliefs. People exhibiting herding bias [12, 16] prioritize information aligns with the majority. Anchoring biases [128, 40] describe humans’ tendency in prioritizing the initial piece of information they receive. These biases can be formulated by addressing how humans form their subjective beliefs. Let e be the event of interest and I be the provided information. Traditional models assume humans are Bayesian, forming their posterior following the Bayes rule $P(e|I) = P(I|e)P(e)/P(I)$. One way for formulate these biases [103] is through modeling humans’ belief updating as $P(e|I) \propto P(I|e)^\alpha P(e)^\beta P(I)^\gamma$ and choosing the values of (α, β, γ) to reflect humans’ different weights in different pieces of information during decision making.

Time-inconsistent planning. Humans often cannot reason about future rewards in a consistent manner. For example, humans might be myopic or boundedly rational, failing to properly reason about future rewards due to cognitive and information limitations. Humans might also inherit time-inconsistent reasoning behavior. For example, when choosing between earning \$10 in 100 days or \$12 dollars in 101 days, most people will choose the latter. However, when choosing between earning \$10 now or \$12 tomorrow, many people will change their decisions to the former. This example illustrates *present bias* [97], an common example of humans’ time-inconsistent panning. These time-inconsistent biases can be modeled by introducing a *discounting function* $d(t)$ that captures humans’ behavior in weighing future rewards. Let R_t denote the expected reward at time t , human’s perceptions of the long-term rewards can be modeled as $\sum_t d(t)R_t$. For example, the standard model often set $d(t) = \gamma^t$ with $\gamma \in (0, 1]$. To model myopic or bounded rationality, we can set $d(t) = \gamma^t$ for all $0 \leq t \leq \tau$, and $d(t) = 0$ for all $t > \tau$. For present bias, one common model is hyperbolic discounting: $d(t) = \frac{1}{1+kt}$ for some pre-specified $k > 0$.

3 Proposed Research

3.1 Thrust 1: Developing Foundations for Learning from Behavioral Data

This thrust aims to develop computationally practical, theoretically sound, and empirically grounded foundations to learn from human behavioral data. In this learning setup, we have access to the observations (s_t, a_t) , indicating human action a_t at state s_t , generated from the *interactions* between humans \mathcal{B} and the environment R .¹ The interactive nature of this setup poses challenges for



learning: Computationally, the learning problem has to address a substantially larger learning space. Theoretically, there could exist scenarios where learning is infeasible. For example, humans tend to choose actions with higher empirical rewards, which results in datasets with excessive *exploitation* and insufficient exploration. Such imbalance could be exacerbated by human biases, like herding bias that attributes higher perceived utility to options chosen more frequently (i.e., rich-get-richer effect). Such scenarios might yield datasets that fail to provide a representative distribution necessary for learning, as illustrated in my prior work [118]. Furthermore, with the rapid progress of generative AI, such as large language models (LLMs), we anticipate it will be deeply integrated into data generation, and therefore it creates pressing needs to incorporate the impacts of generative AI when learning from behavioral data.

¹We use \mathcal{B} to represent the general human models and abuse the notation R to represent general environment parameters, not just rewards. The discussion in this thrust also applies to (a simpler setting of) supervised learning, where we observe the feature-label pairs generated by humans $\{(x_n, y_n)\}_{n=1}^N$ and aim to undercover the latent mapping from features to labels.

To address these challenges, this thrust will start with learning from human behavioral data. We aim to establish provable and practical methodologies for jointly inferring \mathcal{B} and R from human behavioral data (**Task 1.1**). In collaboration with psychology researchers, I will conduct human-subject experiments to deepen our understanding of human behavior in contexts where ML is increasingly integrated into daily decision-making processes (**Task 1.2**). Lastly, I will turn our attention to generative AI and tackle the challenges arising from the growing involvement of generative AI in the data generation process (**Task 1.3**).

Prior work. The proposed activities in this research thrust will be built on the PI’s extensive prior work in crowdsourcing [46, 49, 50, 52, 53, 76, 120, 29, 30], where one key research theme is to infer ground truths from noisy human data. I will extend the standard models assuming humans exhibit zero-mean noises to general human behavioral models. The PI’s recent works on incorporating behavioral models motivated by psychology literature in the learning frameworks [118, 138, 37] and the experience in conducting human-subject experiments [52, 120, 29, 30, 85] will be the building blocks of the proposed research.

3.1.1 Task 1.1: Developing provable and practical algorithms to learn from behavioral data

This task aims to develop computationally practical and theoretically sound algorithms to learn from behavioral data. I aim to theoretically characterize the conditions that make learning feasible, devise efficient algorithms, and implement strategies during data collection to enable efficient learning.

Theoretically characterizing conditions for feasible learning. My prior work [118] showed that there exist scenarios in which learning from behavioral data is infeasible even with infinitely many data observations. Therefore, the first goal is to theoretically characterize the conditions of human models and environments that facilitate feasible learning. I propose to employ techniques from stochastic approximation [107, 39]. The main idea is to model the state realizations over time as a random variable, resulting from the interactions between human behavior and the environment. If a bijection exists between a pair (\mathcal{B}, R) and the state at convergence (a weaker condition might be sufficient), we can infer (\mathcal{B}, R) from the converged state, indicating the feasibility of learning. Therefore, by analyzing the convergence and convergence rate of the state trajectory, we can characterize the conditions for the feasibility and complexity of learning. Moreover, since no models can perfectly capture human behavior, I will also examine the *robustness* of our results, i.e., how the inaccuracies in human models propagates to errors in learning through sensitivity analysis.

Designing computationally efficient algorithms. Even when learning is feasible, we still need to confront computational challenges due to a larger learning space. To tackle this, I plan to adopt, examine, and compare several approaches. First, I will presume partial access to true environment parameters R_t (e.g., some rewards are known in MDP), e.g., through domain knowledge or historical data, and then implement a two-stage learning process (i.e., infer \mathcal{B} using partial R_t then infer full R with the inferred \mathcal{B}). Second, I will impose suitable constraints to reduce the learning space, for instance, by leveraging smoothness constraints or applying domain knowledge on belief models and reward bias models. Lastly, I will resort to sampling and variational techniques, such as Gibbs sampling, to approximate the inference problem.

Taking interventions or increasing diversity during data collection to enable improved learning. One of the main reasons leading to infeasible learning in our setting is the human tendency to engage in *exploitation*, which results in under-represented datasets. Based on this observation, I plan to explore methods to increase the amount of *exploration* in behavioral data (i.e., having humans take potentially suboptimal actions to gather information) during the data collection process. First, I will quantify the impact of the exploration amount on learning efficiency. I will initially adopt an *epsilon-first* approach [126], quantifying the minimum amount of exploration necessary to make learning feasible. Subsequently, I will explore the possibility of reducing the amount of exploration required by strategically deciding when to explore. Second, I will examine the relationship between the diversity of human behavior in the data and the learning efficiency. Recent literature [99] has indicated that inherent diversity in the data could render exploration unnecessary in bandit learning. I aim to extend these findings to our setting, investigating whether and to

what extent increasing diversity in our dataset could facilitate more efficient learning.

3.1.2 Task 1.2: Conducting experiments to understand human behavior in the age of ML

This task focuses on examining real-world human behavior through human-subject experiments. In addition to validating human models and evaluating the proposed approaches, the primary goal of this task is to enhance our understanding of human behavior in settings where ML is pervasively embedded in the decision-making process. In the previous task, I start the investigation by leveraging existing behavioral models from the literature of psychology. Although these models are supported by extensive empirical evidence, they are primarily developed before ML becomes pervasive and widely recognized by the general population. Meanwhile, when people become aware that they are interacting with ML, their behavior might differ (e.g., Microsoft Chatbot Tay). My recent work [71] has demonstrated this phenomenon. We show that when people know their behavior will be used to train ML, they are willing to forgo rewards to ensure that the trained ML exhibits fair behavior. As ML continues to gain more societal attention, it becomes crucial to examine and understand the shifts in human behavior as ML becomes integrated into our daily lives.

Understand human behavior with the presence of ML. I will conduct behavioral experiments to examine whether and how the presence of ML changes human behavior. The results will improve our understanding of human behavior with the presence of ML. It also serves as an improved foundation for addressing the tasks of learning from human behavioral data. To conduct the research, following the standard literature, I will start by utilizing social games, such as the ultimatum game [89], dictator game [36], prisoner’s dilemma [9], to examine human behavior with the presence of ML. These social games provide succinct abstractions of human behavior and interactions in different contexts and are useful as the starting point towards a comprehensive understanding of humans. I will recruit participants from crowdsourcing platforms, e.g., Amazon Mechanical Turk or Prolific. In particular, I plan to vary the following independent variables in the experiment design and measure human responses as the dependent variables. Standard statistical tests (such as ANOVA and postdoc t-tests) will be conducted to examine the significance of the observations.

- Whether humans are explicitly interacting with ML. We hypothesis that humans are more likely to care more about ethics (e.g., being fair) when their partners in the game are other humans than ML.
- Whether human decisions will be used to train ML used to play with future players. We hypothesize humans are willing to sacrifice rewards to make the future ML behave in a more *ethical* manner.
- The context of the game, environment, and ML. For example, whether the trained ML will be playing with people they view favorably in the future. Whether the ML training mechanism is known to people.

For the research activities in this task, I will collaborate with Dr. Wouter Kool in the department of Psychology and Brain Sciences at WashU. Dr. Kool and I are currently co-advising a PhD student, Lauren Treiman, with whom we have generated the preliminary result [71] for this task (i.e., varying conditions on ML training in the ultimatum game). The proposed research will enable us to obtain a more comprehensive understanding of human behavior when ML is integrated in all aspects of decision making.

3.1.3 Task 1.3: Incorporating generative AI in learning from behavioral data

The rise of generative AI, such as large language models (LLMs), is significantly reshaping the manner in which we approach and solve problems. Particularly, in the context of learning from behavioral data, recent research has reported that LLMs outperform human crowd workers in annotating data for certain tasks [42, 34]. As generative AI becomes increasingly prevalent, we anticipate that these models will play a pivotal role in shaping behavioral data generation. At the same time, it has been noted that LLMs can exhibit a range of biases [6, 98]. Therefore, in this task, I aim to provide a deeper understanding of the *behavior* of generative AI, such as LLMs, with the aim of integrating them into our learning framework.

One of the main challenges in incorporating generative AI is due to its black-box nature. In parallel to the growing efforts to address the explainability and transparency of generative AI [73], I will adopt a

behavioral approach, treating generative AI as a behavioral agent, to understand and incorporate its behavior in our learning framework. It is worth noting that given the rapid and ongoing evolution of generative AI, this task signifies a long-term and continuously evolving research agenda. We believe that addressing this is of paramount importance, especially as we approach a potential era where generative AI is ubiquitous

Empirically examine and model the behavior of generative AI. I plan to empirically examine the *behavior* of generative AI. I will begin by characterizing AI behavior using standard human behavioral models, allowing for a direct comparison with human behavior. For instance, our preliminary results suggest that ChatGPT demonstrates behavior similar to humans, particularly in its willingness to sacrifice reward to promote fairness, as seen in the context of the Ultimatum game. Considering generative AI is initially trained on human data, it is both interesting and useful to understand to what extent it mimics human behavioral patterns in different contexts. Moreover, as AI might exhibit distinct behavioral characteristics, I plan to develop new models that provide explainable insights into AI’s decision-making processes.

Theoretically characterize the capacity of generative AI. Building on our understanding of the behavior of generative AI, I will utilize the theoretical insights from Task 1.1 to assess whether learning is feasible using data from generative AI *alone* in a given task domain. If feasible, it implies that the generative AI has sufficiently encoded the problem domain in its models, potentially obviating the need for human involvement in that specific task. This approach offers a perspective on the competence of generative AI.

Leveraging both humans and generative AI to achieve efficient learning. In instances where learning is infeasible using solely AI-generated data, I will examine methods to incorporate data from humans to enhance the learning process. I intend to draw from approaches developed in Task 1.1 to refine the data collection process. Specifically, by viewing generative AI as a group of behavioral agents with distinct behavioral patterns, I will investigate which types of supplemental behavioral data from humans are most likely to enable effective learning. This will be guided by our findings on the relationship between *diversity* in the dataset and the efficiency and feasibility of learning.

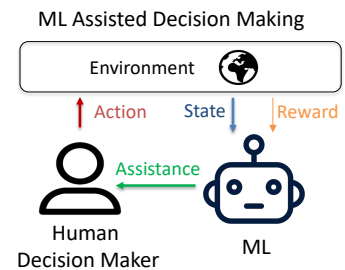
3.2 Thrust 2: Designing Behavior-Aware Assistive ML to Improve Human Decision-Making

Humans often make suboptimal decisions, especially in complex decision-making environments, and often need to engage in “on-the-job-training,” i.e., learn to make better decisions while making these decisions [101, 114, 13]. Conversely, the rapid advancement of ML suggests its potential of enhancing humans’ performance and speeding up their learning in decision making settings with ML assistance, as demonstrated by groundbreaking tools like ChatGPT. In this research thrust, our goal is to develop a framework for ML-assistive decision making that takes human behavior into account. The focus is to determine when and what assistance ML should offer, given a limited amount of interventions. In this setup, ML provides recommendations to humans, who make the final decisions. The objective of ML here is to *augment*, rather than *replace*, humans in the decision-making process.

Designing ML assistance serves dual purposes. First, when deploying ML assistance during human decision making, it augments human decision making, resulting in better outcomes. Second, if we compute the set of ML assistance offline, frequent instances of assistance can pinpoint common errors humans tend to make in the decision-making process. Consequently, these insights not only hold potential as training materials but also carry significant implications for educational practices, as we discuss in Section 4.1.

The ML assistance framework. To make the discussion more concrete, we formulate the ML assistance framework that we will work on in Tasks 2.1-2.2. We will explore extensions to this framework in Task 2.3.

Suppose the human decision maker is solving a decision making problem formulated as an MDP, characterized by the tuple $\langle S, A, T, R \rangle$. Let the human decision-making policy be $\pi_B(a|s)$, representing the probability for the human to choose action a at state s without assistance. The goal of ML is to maximize



the total rewards derived from human actions by providing assistance. Let ML’s assistance policy be $\rho(a|s)$, denoting the probability for ML to recommend action a at state s ,² and $\theta(s)$ be the *reliance policy* denoting whether the human adopt ML assistance at state s . We will start by assuming human reliance policy θ is known in task 2.1 and examine θ in task 2.2. Now let $(\pi_B \oplus \rho \oplus \theta)(a|s)$ be the final human policy with ML assistance, determined by π_B, ρ, θ jointly, e.g., $(\pi_B \oplus \rho \oplus \theta)(a|s) = (1 - \theta(s))\pi_B(a|s) + \theta(s)\rho(a|s)$, the ML’s assistance design problem is then to choose the assistance policy $\rho(a|s)$ to maximize the total expected reward within the pre-defined constraints of ML assistance policy. One natural example of the constraint would be to ensure ML does not intervene human decision-makers too much, i.e., the distance $D(\pi_B, \rho)$ between human policy and ML policy is small for some distance measure D .

Prior work. The proposed activities in this research thrust are grounded in the PI’s extensive prior work. Notably, the problem design aligns with a *Stackelberg game*, where ML initially determines the policy for providing assistance, and humans subsequently decide their course of action based on this assistance. The PI has explored the application of Stackelberg games across various domains, such as contract design [54], learning with strategic responses [123], Bayesian persuasion [25, 122, 37], and environment design [138]. In addition, the PI has substantial expertise in bandit learning [54, 76, 118, 122] and robust learning [123], which serve as technical foundations for addressing the problems of learning and robust design.

3.2.1 Task 2.1: Developing efficient approaches for designing ML assistance

In this task, the goal is to design ML assistance policy accounting for human behavior. I will start with *low-complexity* environments where the optimal decision policy is algorithmically derivable using standard methods (such as value iteration). However, since the goal of the ML assistance is to improve human decision making with limited interventions, we need to consider the behavior of human decision maker, leading to a more complex design problem. I will first presume known human models and propose algorithms to identify the optimal assistance policy. I will then relax the low-complexity environment and known human model assumptions, proposing data-driven approaches for *high-complexity* environments and developing algorithms to infer human models when unknown.

Algorithmic approaches. I will start with low-complexity environments. Consider the standard rational human assumption, i.e., choosing the action with the highest utility with probability 1. When putting this decision function back to the design of ML assistance, the objective is non-continuous and the problem is NP-hard to solve as shown in my prior work [138]. On the other hand, when we consider the discrete choice model, i.e., the decision function is in the form of a continuous softmax function. With this human model, the objective of the optimization problem is continuously differentiable, and first-order optimization techniques might be applied. The above discussion highlights the need to understand how different human models impact the design of ML assistance and my proposed approaches: (1) When the human decision models are differentiable (e.g., discrete choice model), I will leverage first-order optimization methods and characterize the computational complexity and convergence to the optimal solution with different human models. (2) When the human models are not differentiable (e.g, expected utility theory), I plan to utilize the techniques from algorithmic information design [31, 35, 10] (including my own work [25, 37]). This approach utilizes the duality theory to characterize the properties of the optimal solution, which could help identify conditions for computationally feasible solutions to exist. I will also utilize techniques such as soft-max relaxations to derive approximation algorithms in the case that when the optimization is NP-hard.

Data-driven approaches. For high-complexity environments and known human models, I propose to leverage data-driven approaches to design ML assistance. I will extend the self-play [111, 24, 139] that optimizes decision policy in MDP to incorporate human models to optimize ML assistance. Specifically, I propose a neural-network-based structure that consists of two modules: the ML’s optimization module and the human

²We discuss extending the assistance space beyond the human action space in Task 2.3. When $\rho(a|s) = \pi_B(a|s)$ for all a , it means there is no ML assistance in state s .

models. The ML’s optimization follows the traditional neural-network-based structure, taking the details of a problem instance as input and outputs an assistance policy. The main difference compared with prior work is that we have incorporated human models, either in an analytical closed-form or a data-driven form in the optimization structure. The human models are treated as a black box for the ML’s optimization module and is fixed before we begin training. Given the assistance policy output by the ML’s optimization module, we can compute the *loss* (the inverse of the reward of applying the assistance policy) by applying the assistance policy with the human models in the environment. For optimizing the assistance policy, I’ll adopt the approach of using deep learning for optimization [32, 93]: Draw problem instances from a pre-specified distribution and perform stochastic gradient descent to minimize the loss function (applying soft-max approximation for non-differentiable objectives). I will examine the empirical performance of this neural-network based approach with different settings of human models, environments, and instance distributions.

Bandit learning approaches for unknown human models. While the above optimization architecture is general and powerful, it requires us to estimate the *loss* for the assistance policy in each iteration. In settings where the human models are unknown, we won’t be able to infer the final human decisions to obtain an accurate loss estimation. To address this, I consider the setting in which the ML can sequentially interact with human decision makers in the environment, observe their responses, and adaptively update the assistance policy over time. This leads to an *online learning* setting in which we need to address the classical trade-off between exploitation (choosing policy with the highest estimated payoff) and exploration (choosing policy with uncertain payoff to obtain information), which can be formulated as a multi-armed bandit problem [70, 8, 20]. I plan to explore the usage of bandits in this setting. The main challenge is that the space of arms (i.e., the space of assistive policies) is large/infinite and could require too many explorations for bandit algorithms to be useful. To explore this challenge, I plan to adopt the technique in my prior work on leveraging the similarities between arms in bandit learning [54]. The key intuition is that, if two policies lead to similar payoffs, they are considered “similar” arms, and we propagate the information we learned on one policy to other similar policies to achieve efficient learning. To quantify the arm similarity, I plan to leverage domain knowledge to characterize the problem structure (e.g., abstracting key properties of human models and environment states) to reduce the problem space. Our goal is to identify conditions for bandit approaches to work and develop corresponding algorithms.

3.2.2 Task 2.2: Understanding human reliance on ML assistance with human-subject experiments

This task aims to conduct investigations of humans’ trust and reliance on ML recommendations in the setting with sequential decision making. The previous task has assumed that human reliance on ML assistance, $\theta(s)$, is known and given. However, in practice, appropriately formulating $\theta(s)$ is not trivial and not well understood. While there has been a growing line of literature in understanding humans’ trust and reliance on ML [137, 77, 105, 140, 75, 130], including the PI’s work [85], existing studies mostly focus on the one-shot decision making scenarios. Limited is known about how humans trust and rely on ML assistance in *sequential decision making settings*.

Proposed research. In collaboration with Dr. Ming Yin, a leading expert in human trust and reliance on AI at Purdue University, I will conduct randomized human-subject studies to understand how human decision makers’ reliance on ML are influenced by various factors under the sequential decision making setting. In particular, consistent with theoretical models previously proposed for human-automation interaction [55, 108], I expect humans’ adoption of ML advice under sequential decision making settings can be influenced by factors related to *humans*, *ML*, and the *environment*. I will conduct experiments to understand:

- How factors related to ML, including the presentation format of ML recommendations, the provision of ML explanations, and the human-likeness of ML, influence humans’ adoptions of ML advice?
- How factors related to the decision making environment, including the variability and complexity of the environment, influence humans’ adoptions of ML advice?

- How factors related to humans, including their risk attitudes, their value similarity with ML, and their subjective perceptions of ML trustworthiness, influence humans’ adoptions of ML advice?

General experimental designs. For each human-subject experiment, I will start by designing experiment that only a single independent variable varies. That is, different experimental treatments will be created corresponding to different “levels” of the independent variable (e.g., timing of ML recommendations, type of ML explanations, human-likeness of the ML policy). For dependent variables, I will record whether human participants decide to rely on the ML’s decision recommendations to estimate $\theta(s)$, as well as their final decision making performance. In addition, to align with the AI trust literature, I will ask human participants to self-report their perceived trust level in the ML agent both at a fixed interval (e.g., after every 5 decisions are made) and at the end of the experiment. I will also have the human participants complete a two-phase experiment, in which they make sequential decisions in the first phase with the assistance of the ML agent, while they make sequential decisions on their own in the second phase, and we can record their decision making performance in the second phase to understand if human decision makers can effectively learn from the ML agent in the first phase. After collecting the measurements on all the dependent variables, we can conduct statistical tests across treatments to examine if the independent variable varied in the experiment affects decision makers’ adoption of ML advice and subjective trust on ML, sequential decision making performance, and learning outcome. Moreover, additional experiment can be carried out to vary multiple independent variables simultaneously, which will allow us to understand how they interact with one another to affect the dependent variables of interests.

3.2.3 Task 2.3: Towards a broader ML assistance framework

This thrust starts with an ML assistance framework aligning with the recent literature in ML-assisted decision making [138, 13, 21]. While the previous two tasks focus on addressing the key research questions of realizing ML assistance in practice, including incorporating general human behavioral models, addressing computational/information constraints, and understanding human reliance on ML assistance, this task holds a distinct ambition. Inspired by the increasing reliance of humans on generative AI tools like ChatGPT, our goal here is to broaden the ML assistance framework. We aim to extend the ML assistance framework and address different interaction patterns between humans and assistive ML.

General assistance space. In the framework specified earlier, ML assistance policy is represented as $\rho(a|s)$, i.e., the space of ML assistance is the same as humans’ action space. However, in a more expansive setup, ML can offer a wider range of assistive information, guiding humans in their final decision-making. In this broader context, we can define ML’s assistance space as \mathcal{K} . Consequently, the assistance policy is represented as $\rho(\sigma|s)$, where $\sigma \in \mathcal{K}$. With this extension in place, the challenge arises in determining how humans utilize the offered assistive information. One approach is to assume humans would form a posterior belief, denoted as $\mu(\mu_0, \sigma)$, about the action outcomes, where μ_0 is the prior. With this posterior belief, humans will choose actions based on their (possibly skewed) perceived expected utility. Note that under the assumption that humans update their posterior beliefs in a Bayesian fashion and make rational action choices, this scenario can be likened to the traditional information design challenge, termed Bayesian persuasion [62]. In this task, my aim is twofold: First, to move away from the Bayesian rational assumption in this framework when conceptualizing ML assistance. My preceding works [122, 37] are pioneering efforts in this vein. Subsequently, I will harness empirical insights from the realms of explainability [106, 78, 44, 102, 64, 95] and AI trust [137, 77, 105, 140, 75, 130]. This will further enable us to sculpt more grounded models depicting the interplay between human decision-making and ML-assisted guidance.

Human-initiated assistance. So far, we have focused on the *push-based* ML assistance, where ML determines when to offer assistance and actively *pushes* it to human decision-makers. An alternative paradigm is the *pull-based* ML assistance, in which ML remains passive, responding only when humans request assistance. This shift in interaction between humans and assistive ML introduces an additional layer of complex-

ity to the design of ML assistance. Specifically, ML must anticipate when humans might seek assistance to decide the most appropriate help to provide. For instance, if humans frequently request assistance, ML can simply provide support following the optimal policy. Conversely, if humans seldom seek help, ML needs to evaluate whether the recommended action might lead users into situations where they are prone to mistakes. To incorporate this into our ML assistance framework, we can define a model $P_{req}(s)$, which represents the probability for users to initiate requests for assistance. When $P_{req}(s)$ is known, we can incorporate this representation in our formulation and utilize similar methodologies. However, when $P_{req}(s)$ is unknown, ML needs to infer its values. To navigate this challenge, I will utilize both bandit and standard inference techniques. Moreover, I plan to investigate a hybrid interaction pattern that defaults to the pull-based approach but can shift to push-based assistance in critical situations, such as high-stakes scenarios.

3.3 Thrust 3: Integrating with Domain Applications

In research thrusts 1 and 2, the goal is to develop a framework for behavior-informed machine learning, incorporating human behavior in the design of ML systems. While the framework is intended to be general, deploying the framework in specific domain applications may introduce various domain-specific challenges. For instance, when allocating scarce societal resources for homelessness prevention, it is important not only to maximize the effectiveness of these resources but also to ensure that the allocation of resources is *fair and equitable* across different social groups. When designing decision support systems for airplane pilots, in addition to maintaining decision efficiency, *safety* is of the utmost importance.

In this thrust, I aim to collaborate with domain experts to tackle practical challenges when deploying this framework in domain applications. In particular, the proposed research will be tailored for use in the domains of homelessness prevention (with Prof. Patrick Fowler at the Brown School of Social Work) and flight pilot augmentation (with Boeing). In the long term, I plan to harness the interdisciplinary efforts at WashU to expand this research into other application domains, including the Division of Computational and Data Sciences (DCDS), the Center for Collaborative Human-AI Learning and Operation (HALO), and the Transdisciplinary Institute in Applied Data Sciences (TRIADS) at WashU that the PI is an active member in. These cross-disciplinary endeavors will help ensure that our research findings are practically applicable across various domains, thus promoting their adoption and potential for impact.

3.3.1 Task 3.1: Domain application: Data-driven decision support for homelessness prevention

This task extends my existing collaboration with Prof. Patrick Fowler on developing algorithmic solutions to homelessness prevention [28] to the scope of data-driven decision support for homelessness prevention. The problem of homelessness, a longstanding societal issue, presents significant personal and communal repercussions. Local systems dedicated to addressing homelessness often face a scarcity of resources, making it challenging to fulfill the demand for housing support. The current decision-making processes for distributing these limited resources are largely unexplored [17, 38, 110], leaving room for improvement in terms of both efficiency and equity. This opens up two important research directions that align with this CAREER plan: First, we can utilize historical data to understand the impacts of past resource allocation, thereby allowing us to derive insights to optimize future decisions. Secondly, by harnessing the power of ML, we can provide decision support for human decision makers in deciding the resource allocation.

Account for human behavior when learning from past data. There is a growing effort to use data-driven approaches to inform decision-making policies in homelessness prevention [41, 67, 69]. Specifically, Prof. Fowler has been involved in the St. Louis Regional Data Alliance [1], an initiative that aims to curate community data to improve community health, such as reducing homelessness. Building on this effort, Dr. Fowler and I have been co-advising a PhD student, Alex DiChristofano, in conducting preliminary analyses of St. Louis regional data. We have identified two types of human behavior that could inject biases into the data. The first comes from the recipients of resources. In homelessness prevention, when people seek help, they are not immediately assigned resources due to the resource scarcity. Instead, they are placed on a

waitlist and only receive resources when resources become available. This waiting process creates unequal *drop-out* rates across social groups, e.g., we found that females are more likely to leave the system before resources become available. Failure to account for this drop-out inequality could lead to biased predictions of resource efficacy. The second type of behavior that needs to be taken into account comes from the parties (e.g., social workers) that decide how to allocate resources. While there are general guidelines in the decision-making policy, the past data largely reflects the decision-makers' judgments. In this task, we aim to identify and incorporate this human behavior during the training of ML based on past data.

Designing decision support. In the decision-making process for allocating resources for homelessness, there isn't a clear right or wrong answer. Social workers often need to balance multiple ethical principles, such as prioritizing outcomes (reducing homelessness) or prioritizing the most vulnerable individuals [68]. When designing decision support systems, we must consider decision-makers' preferences and constraints. In this task, we will work with local homelessness service providers, the St. Louis Area Regional Commission on Homelessness (SLARCH) – a nonprofit organization that coordinates homeless service provision across the St. Louis region. By conducting qualitative surveys and interviews, we aim to gain better insights into their decision-making process, their objectives in decision-making, and the types of decision support needed to inform the design of our assistive ML. Furthermore, we will work with social workers, the decision-makers in the field, recruited through SLARCH, to evaluate and deploy our research.

3.3.2 Task 3.2: Domain application: Decision support for airplane pilots

This task aims to launch our newly initiated collaboration with Boeing in designing decision support for pilot decision-making. In this application domain, safety is of paramount importance, in addition to efficiency. To make the discussion more concrete, we will discuss the design of pilot augmentation to address runway incursions – a significant aspect of runway safety. Runway incursion [2] refers to an incident involving an incorrect presence of an aircraft, vehicle, or person on a runway designated for take-off or landing. In severe cases, runway incursions could lead to tragic events. Given the gravity of this problem, there has been research devoted to avoiding such incursions, including accident prediction [116, 112, 43] and system design to detect obstacles and alert pilots [56, 91, 94, 134]. Meanwhile, the Federal Aviation Administration (FAA) have reported that pilot behavior is involved in 65% of all runway incursions [3]. Therefore, in this task, aligning with this CAREER plan, we plan to adopt a behavior-informed approach in addressing the runway incursion problem. We will examine existing datasets and behavioral data from simulated platforms to identify pilot behavioral patterns in the context of runway incursions. Moreover, we will design decision support that provides interventions to prevent runway incursion events.

Proposed research. For the question of learning from behavioral data, we will leverage two data sources. The first is the public ASRS (Aviation Safety Reporting System) dataset, FAA's voluntary confidential reporting system that accepts confidential reports of near misses or close call events in the interest of improving aviation safety. This public dataset will enable us to identify generic characteristics for runway incursions. We will then leverage the flight simulator X-Plane, that WashU has acquired in the previous collaboration with Boeing, to collect individual behavioral data for identifying personalized behavioral patterns in runway safety. After identifying the behavioral patterns, we will design decision support systems that aim to maximize decision efficiency (e.g., time for departing/landing) while imposing safety constraints. The study will be initially conducted in an academic setting, recruiting general population (e.g., college students) in running the flight simulator. After developing the results, in collaboration with Boeing, the study will be extended to other contexts (e.g., inflight weather encounters, wake turbulence encounters), and the evaluations will be conducted with domain experts and real pilots through simulations/surveys.

3.4 Evaluation Plan

The proposed research will span five years. The tasks in Thrust 1 and 2 have been organized in a way that can be performed in a sequential manner. I will perform the tasks in Thrust 3 after we have initial results for

the first two thrusts. For the evaluation of the proposed research, there are three main components:

- **Algorithm and theory:** For task 1.1-1.2 and 2.1-2.2, I will develop new algorithms and theories. To evaluate our results, I will derive the performance guarantees (regret bounds or convergence rate) and analyze the computational complexity of the proposed algorithms. We will perform equilibrium analysis to characterize the human behavior in the equilibrium structure. Simulation will also be performed to evaluate the algorithm performance under the conditions both when users follow our proposed models and when users do not exactly follow to test for robustness of our proposed algorithms.
- **Data collection:** Task 1.3 and 2.3 involve collecting data using human-subject experiments. With collaborations with experts in psychology and HCI, I will follow the best practice in conducting the experiments, including pre-registering the hypothesis and performing appropriate statistical tests (e.g., ANOVA, post-hoc t-tests, mixed effects model). The collected data will be made publicly available to the research community. I believe the large-scale behavioral data would be of important research value.
- **Deployment:** For tasks in Thrust 3, I aim to deploy the proposed research in domain applications. In addition to the evaluations above, I will work with domain experts to develop our evaluation plan and solicit feedback of the proposed framework through interviews/surveys.

4 Education Plan

This CAREER proposal aims to leverage the research effort to achieve my long-term education goal: data-driven personalized education. I will disseminate the research outcome to different education levels, including designing a new graduate-level course, engaging undergraduate students in research, and host workshops for high-school teachers and students. Moreover, I will devote effort to broadening research participation.

4.1 Education Thrust 1: Towards Data-Driven Personalized Education

My long-term vision in education is to develop data-driven methods that enable personalized education, i.e., designing personalized curriculum and assistance that improves individual learning with data-driven approaches. This vision aligns with this CAREER plan on designing ML that learns from human behavioral data and assisting humans. As a starting point to realize this vision, we have started to conduct research in the domain of Chess to develop personalized ML assistant. In collaboration with Kassa Korley [83], who holds the title of International Master and was the youngest African American to earn the title of National Master in the US, we have investigated the question of curriculum design, i.e., what set of moves should be provided to assist Chess players based on their skills, using data-driven approaches. In particular, leveraging the abundant amount of human play data in online Chess platforms (Lichess.org), we have developed ML models that can mimic human plays at different skill levels. We then leveraged both the idea of designing ML assistance in this proposal and curriculum learning [15, 132, 115] to identify the curriculum mostly likely to improve players with given skill levels. Our preliminary results, showing that the approaches can identify curricula that align with domain knowledge and improve win rate, holds potential in designing personalized tool to improve human learning in Chess.

I will also collaborate with Prof. Dennis Barbour, through co-advising a PhD student, Robert Kasumba. Prof. Barbour has employed data-driven approaches to explore the connection between students' mathematical learning skills and general executive function skills, such as cognitive flexibility, working memory, and inhibitory/attentional control. Leveraging his expertise, the goal of this collaboration is to improve personalized education in the setting of enhancing mathematical skills.

Evaluation plan. We will initially perform simulations to evaluate our approaches, examining whether our curriculum improves ML models trained on human data. For real-world deployments, we have recently obtained WashU IRB approval to recruit chess players to examine the effectiveness of our approaches.

4.2 Education Thrust 2: Course and Teaching Development

The research goal of the PI is to combine the strengths of both humans and machine learning (ML) to solve tasks neither can solve alone. To achieve this goal, we need to advance our understanding of ML, humans, and the interactions between them. Correspondingly, the education goal of the PI is to prepare students on these fronts. The PI plans to introduce a new graduate-level course *Human-AI Interaction and Collaboration*. In addition to the general coverage of ML and human modeling (from behavioral economics, psychology, and HCI), there will be two main themes for the course topics. First, we will cover and discuss human-in-the-loop machine learning, addressing the techniques of incorporating humans in the learning process to advance machine learning. Second, we will discuss topics with a human-centered focus, including how humans process information from ML (such as interpretability, trustworthiness, and topics explored in this proposal) and how ML impacts human welfare (such as fairness, privacy, and ethical concerns). We will also include practical domain applications in social sciences and healthcare in the course materials (in the form of assignments, projects, or guest lectures) by leveraging the Division of Computational and Data Science (DCDS) and the Center for Collaborative Human-AI Learning and Operation (HALO) at WashU.

Evaluation plan. The PI will work with the Center for Integrative Research on Cognition, Learning, and Education (CIRCLE) at WashU to develop evaluation plan for the proposed course. We have allocated budgets for the evaluation service. The evaluations will be conducted based on multiple metrics, including whether students obtain firm grasp of the subject (by constructing a knowledge inventory) and whether the course motivates students in applying the knowledge in different domains.

4.3 Education Thrust 3: Broadening Research Participation

Outreach to high-school teachers and students. The PI will work with the Institute for School Partnership (ISP) at WashU to design outreach activities. The goal is to provide professional developments for high-school teachers and broaden the dissemination of research ideas, and to cultivate next-generation scientists/engineers through exposing high-school students to academic research and stimulating their interests in computing. In particular, we will work with the ISP for the *Teacher-Researcher Partnership*, under which teachers work in the faculty’s lab for 4-6 weeks in the summer, with the goal of learning and translating research ideas into lessons at grade level. We plan to host one teacher in each of the first two summers. Based on the partnership outcomes, we will participate in the *Hot Topic Series* at ISP and invite around 20 high-school teachers to disseminate the curriculum design to maximize the potential outreach.

The PI will also join force with existing efforts at the McKelvey School of Engineering, which has conducted a summer camp in Summer 2022 for local high school students of low-income backgrounds. This summer camp is planned to become an annual event. The PI will annually host a one-day summer workshop “Human-Centered Machine Learning” within this framework. The workshop will include a broad overview of machine learning and human behavior and engage students in group projects guided by Ph.D. students. We will prepare datasets and ML modules for students to explore the impact of human behavior in the design of ML, both for how human behavior leads to learning (how biased dataset leads to biased learning outcome) and how ML can assist humans in overcoming biases.

Engagements of traditionally underrepresented students. The PI is committed to recruiting female and underrepresented minority (URM) students. The PI is currently advising 5 PhD students, with whom one is female and another one is African American. The PI has also worked with 6 female and URM undergraduate/master students (out of 13 students that worked with the PI) at WashU so far. Among the 6 students, four have continued their graduate studies after graduation (at Stanford, Duke, Penn State, and Cornell), one went to the industry (at Google), and one is still in the undergraduate program. The PI will leverage the institutional effort for engaging female and URM students. In particular, WashU is committed to the goal of increasing the representation of women at the Ph.D. level. The CSE department, the McKelvey School of Engineering, and the Provost’s Office of Diversity together fund a Platinum Sponsorship of Grace

Hopper. Through WashU Summer Engineering Fellowship (WUSEF), which provides funds for students from backgrounds underrepresented in the STEM fields to perform summer research, the PI has advised one URM undergraduate student. In addition to working with WUSEF each summer, the PI will work with the Missouri Louis Stokes Alliance for Minority Participation (MOLSAMP), of which WashU is a participating institution, for offering summer research opportunities for minority participation.

Undergraduate research participation. Undergraduate students will be heavily engaged in the proposed research. The PI has been actively involved in the NSF REU site “Big Data Analytics” at WashU. The students the PI advised at the REU site have all continued their graduate studies in the Computer Science field (at UT Austin, Duke, CMU, Yale, and Cornell) after graduation. The PI is committed to annually support REU/WUSEF research projects inspired by this proposal, such as understanding user behavior in computational systems through conducting behavioral experiments or analyzing existing datasets. The PI will also support undergraduate students on independent research projects during the academic year.

Evaluation plan. For outreach to high-school teachers and students, the ISP will provide consultations for evaluation plans. In particular, I will conduct anonymous surveys to high-school teachers/students before and after the event to evaluate their understanding of the topic and their aspirations in pursuing higher-education in STEM. For research engagements with URM, female, and undergraduate students, I will conduct two interviews (before and after) to identify potential areas of improvements.

5 Broader Impacts

The research of designing ML to learn from humans and assist humans creates a wide range of impacts. It impacts the design of a broad range of online platforms with active human participation, including recommendation systems, user-generated content platforms, social networking sites, in improving the way the platform interacts with users. Moreover, as algorithmic decision making gets deployed more widely in policy making, this research contributes to improving decision making for societal issues. In particular, the PI has existing collaborations with Prof. Patrick Fowler at Brown School of Social Work for homeless prevention [27] and with Dr. Jason Wellen at Medical School to apply computational approaches for living donor kidney transplantation [72]. The PI plans to continue and expand the collaborations through the Division for Computational and Data Sciences (DCDS) which brings together the Department of Computer Science & Engineering with the departments of Political Science and Psychological and Brain Sciences in Arts & Sciences and with the Brown School of Social Works. The PI has been co-advising three PhD students (with faculty from Social Work, Psychology, and Biomedical Imaging) through DCDS.

Industry. The research has high potential for practical applications. I will work with industrial partners to translate the research outcome to practice. I have been engaging with Boeing in developing approaches for ML to augment human decision making. I have also been working with the office of industrial relations at WashU on building collaborations with other industrial partners (e.g., including a faculty research award from JPMorgan and ongoing discussion with Waters Corporation) in deploying the research into practice.

Dissemination of results. One of the main research efforts in this proposed research is to collect human behavioral data through multiple sets of large-scale behavioral experiments. We plan to make the collected data publicly accessible to the research community. To disseminate our research results to a broad audience, in addition to regular conference and journal publications, we will publicly release the software implementations of algorithms, simulation test-bed, and models developed in this project. Furthermore, we will disseminate results within the interdisciplinary DCDS program at Washington University through regular interaction with other faculty in the program, as well as its seminar series.

6 Results from Prior NSF Support

Dr. Ho is a co-PI on “FAI: FairGame: An Audit-Driven Game Theoretic Framework for Development and Certification of Fair AI” (IIS-1939677, \$444,145, Jan 2020 to Dec 2023). *IM*: This project provides a general framework for fair decision making and auditing in stochastic, dynamic environments. PI Ho has published six publications in this project [84, 123, 29, 122, 30, 85]. *BI*: The work supports the training of graduate students and the development of new auditing algorithms that have impacts to AI and society.

References

- [1] St. louis regional data alliance. community information exchange. URL <https://stldata.org/project-community-information-exchange/>.
- [2] Runway incursions. URL https://www.faa.gov/airports/runway_safety/resources/runway_incursions.
- [3] Runway incursion totals for fy 2014, 2014. URL http://www.faa.gov/airports/runway_safety/statistics/regional/?fy=2014.
- [4] Pieter Abbeel and Andrew Y Ng. Apprenticeship learning via inverse reinforcement learning. In *Proceedings of the twenty-first international conference on Machine learning*, page 1. ACM, 2004.
- [5] Jacob Abernethy, Yiling Chen, Chien-Ju Ho, and Bo Waggoner. Low-cost learning via active data procurement. In *16th ACM Conf. on Economics and Computation (EC)*, 2015.
- [6] Abubakar Abid, Maheen Farooqi, and James Zou. Persistent anti-muslim bias in large language models. In *Proceedings of the 2021 AAAI/ACM Conference on AI, Ethics, and Society*, pages 298–306, 2021.
- [7] Tal Alon, Magdalen Dobson, Ariel Procaccia, Inbal Talgam-Cohen, and Jamie Tucker-Foltz. Multi-agent evaluation mechanisms. In *Proceedings of the AAAI Conference on Artificial Intelligence*, 2020.
- [8] Peter Auer, Nicolò Cesa-Bianchi, and Paul Fischer. Finite-time analysis of the multiarmed bandit problem. *Machine Learning*, 47(2-3):235–256, 2002. Preliminary version in *15th ICML*, 1998.
- [9] Robert Axelrod. Effective choice in the prisoner’s dilemma. *Journal of conflict resolution*, 24(1): 3–25, 1980.
- [10] Ashwinkumar Badanidiyuru, Kshipra Bhawalkar, and Haifeng Xu. Targeting and signaling in ad auctions. In *Proceedings of the Twenty-Ninth Annual ACM-SIAM Symposium on Discrete Algorithms*, pages 2545–2563. SIAM, 2018.
- [11] Eytan Bakshy, Solomon Messing, and Lada A Adamic. Exposure to ideologically diverse news and opinion on facebook. *Science*, 348(6239):1130–1132, 2015.
- [12] Abhijit V Banerjee. A simple model of herd behavior. *The quarterly journal of economics*, 107(3): 797–817, 1992.
- [13] Hamsa Bastani, Osbert Bastani, and Wichinpong Park Sinchaisri. Improving human decision-making with machine learning. *arXiv preprint arXiv:2108.08454*, 2021.
- [14] Shai Ben-David, Dávid Pál, and Shai Shalev-Shwartz. Agnostic online learning. In *COLT*, volume 3, page 1, 2009.
- [15] Yoshua Bengio, J  r  me Louradour, Ronan Collobert, and Jason Weston. Curriculum learning. In *Proceedings of the 26th annual international conference on machine learning*, page 41  48, 2009.
- [16] Sushil Bikhchandani, David Hirshleifer, and Ivo Welch. A theory of fads, fashion, custom, and cultural change as informational cascades. *Journal of political Economy*, 100(5):992–1026, 1992.

- [17] Molly Brown, Camilla Cummings, Jennifer Lyons, Andrés Carrión, and Dennis P Watson. Reliability and validity of the vulnerability index-service prioritization decision assistance tool (vi-spdat) in real-world implementation. *Journal of Social Distress and the Homeless*, 27(2):110–117, 2018.
- [18] Michael Brückner and Tobias Scheffer. Stackelberg games for adversarial prediction problems. In *Proceedings of the 17th ACM SIGKDD international conference on Knowledge discovery and data mining*, pages 547–555, 2011.
- [19] Michael Brückner, Christian Kanzow, and Tobias Scheffer. Static prediction games for adversarial learning problems. *Journal of Machine Learning Research*, 13(Sep):2617–2654, 2012.
- [20] Sébastien Bubeck and Nicolo Cesa-Bianchi. Regret Analysis of Stochastic and Nonstochastic Multi-armed Bandit Problems. *Foundations and Trends in Machine Learning*, 5(1):1–122, 2012.
- [21] Frederick Callaway, Yash Raj Jain, Bas van Opheusden, Priyam Das, Gabriela Iwama, Sayan Gul, Paul M Krueger, Frederic Becker, Thomas L Griffiths, and Falk Lieder. Leveraging artificial intelligence to improve people’s planning strategies. *Proceedings of the National Academy of Sciences*, 119(12):e2117432119, 2022.
- [22] Sharath R. Cholleti, Sally A. Goldman, Avrim Blum, David G. Polite, and Steven Don. Veritas: Combining expert opinions without labeled data. In *Proceedings 20th IEEE international Conference on Tools with Artificial intelligence (ICTAI)*, 2008.
- [23] A. P. Dawid and A. M. Skene. Maximum likelihood estimation of observer error-rates using the EM algorithm. *Applied Statistics*, 28:20–28, 1979.
- [24] Anthony DiGiovanni and Ethan C Zell. Survey of self-play in reinforcement learning. *arXiv preprint arXiv:2107.02850*, 2021.
- [25] Bolin Ding, Yiding Feng, Chien-Ju Ho, Wei Tang, and Haifeng Xu. Competitive information design for pandora’s box. In *Proceedings of the 2023 Annual ACM-SIAM Symposium on Discrete Algorithms (SODA)*, pages 353–381. SIAM, 2023.
- [26] Vinayak V Dixit, Sai Chand, and Divya J Nair. Autonomous vehicles: disengagements, accidents and reaction times. *PLoS one*, 11(12):e0168054, 2016.
- [27] Zehao Dong, Sanmay Das, Patrick Fowler, and Chien-Ju Ho. Efficient nonmyopic online allocation of scarce resources. In *Proceedings of the 20th International Conference on Autonomous Agents and Multi-Agent Systems (AAMAS)*, 2021.
- [28] Zehao Dong, Sanmay Das, Patrick Fowler, and Chien-Ju Ho. Efficient nonmyopic online allocation of scarce reusable resources. In *AAMAS Conference proceedings*, 2021.
- [29] Xiaoni Duan, Chien-Ju Ho, and Ming Yin. Does exposure to diverse perspectives mitigate biases in crowdwork? an explorative study. In *Proceedings of the AAAI Conference on Human Computation and Crowdsourcing*, pages 155–158, 2020.
- [30] Xiaoni Duan, Chien-Ju Ho, and Ming Yin. The influences of task design on crowdsourced judgement: A case study of recidivism risk evaluation. In *Proceedings of the ACM Web Conference 2022*, pages 1685–1696, 2022.
- [31] Shaddin Dughmi and Haifeng Xu. Algorithmic bayesian persuasion. *SIAM Journal on Computing*, 2019.

- [32] Paul Dütting, Zhe Feng, Harikrishna Narasimhan, David Parkes, and Sai Srivatsa Ravindranath. Optimal auctions through deep learning. In *International Conference on Machine Learning*, pages 1706–1715. PMLR, 2019.
- [33] Glyn Elwyn, Adrian Edwards, Martin Eccles, and David Rovner. Decision analysis in patient care. *The Lancet*, 358(9281):571–574, 2001.
- [34] Zohar Elyoseph, Dorit Hadar-Shoval, Kfir Asraf, and Maya Lvovsky. Chatgpt outperforms humans in emotional awareness evaluations. *Frontiers in Psychology*, 14:1199058, 2023.
- [35] Yuval Emek, Michal Feldman, Iftah Gamzu, Renato PaesLeme, and Moshe Tennenholtz. Signaling schemes for revenue maximization. *ACM Transactions on Economics and Computation (TEAC)*, 2(2):1–19, 2014.
- [36] Christoph Engel. Dictator games: A meta study. *Experimental economics*, 14:583–610, 2011.
- [37] Yiding Feng, Chien-Ju Ho, and Wei Tang. Rationality-robust information design: Bayesian persuasion under quantal response. *arXiv preprint arXiv:2207.08253*, 2022.
- [38] Patrick J Fowler, Peter S Hovmand, Katherine E Marcal, and Sanmay Das. Solving homelessness from a complex systems perspective: insights for prevention responses. *Annual review of public health*, 40:465–486, 2019.
- [39] Noufel Frikha, Stéphane Menozzi, et al. Concentration bounds for stochastic approximations. *Electronic Communications in Probability*, 17, 2012.
- [40] Adrian Furnham and Hua Chu Boo. A literature review of the anchoring effect. *The journal of socio-economics*, 40(1):35–42, 2011.
- [41] Yuan Gao, Sanmay Das, and Patrick Fowler. Homelessness service provision: a data science perspective. In *Workshops at the thirty-first AAAI conference on artificial intelligence*, 2017.
- [42] Fabrizio Gilardi, Meysam Alizadeh, and Maël Kubli. Chatgpt outperforms crowd-workers for text-annotation tasks. *arXiv preprint arXiv:2303.15056*, 2023.
- [43] Jean-Baptiste Gotteland, Nicolas Durand, Jean-Marc Alliot, and Erwan Page. Aircraft ground traffic optimization. In *ATM 2001, 4th USA/Europe Air Traffic Management Research and Development Seminar*, pages pp–xxxx, 2001.
- [44] Riccardo Guidotti, Anna Monreale, Salvatore Ruggieri, Franco Turini, Fosca Giannotti, and Dino Pedreschi. A survey of methods for explaining black box models. *ACM computing surveys (CSUR)*, 51(5):1–42, 2018.
- [45] Moritz Hardt, Nimrod Megiddo, Christos Papadimitriou, and Mary Wootters. Strategic classification. In *Proceedings of the 2016 ACM conference on innovations in theoretical computer science*, pages 111–122, 2016.
- [46] Chien-Ju Ho and Jennifer Wortman Vaughan. Online task assignment in crowdsourcing markets. In *26th AAAI Conference on Artificial Intelligence (AAAI)*, 2012.
- [47] Chien-Ju Ho and Ming Yin. Working in pairs: Understanding the effects of worker interactions in crowdwork. *arXiv preprint arXiv:1810.09634*, 2018.

- [48] Chien-Ju Ho, Yu Zhang, Jennifer Wortman Vaughan, and Mihaela van der Schaar. Towards social norm design for crowdsourcing markets. In *4th Human Computation Workshop (HCOMP)*, 2012.
- [49] Chien-Ju Ho, Shahin Jabbari, and Jennifer Wortman Vaughan. Adaptive task assignment for crowdsourced classification. In *30th Intl. Conf. on Machine Learning (ICML)*, 2013.
- [50] Chien-Ju Ho, Aleksandrs Slivkins, and Jennifer Wortman Vaughan. Adaptive contract design for crowdsourcing markets: Bandit algorithms for repeated principal-agent problems. In *15th ACM Conf. on Electronic Commerce (EC)*, 2014.
- [51] Chien-Ju Ho, Aleksandrs Slivkins, Siddharth Suri, and Jennifer Wortman Vaughan. Incentivizing high quality crowdwork. In *Proceedings of the 24th International Conference on World Wide Web*, pages 419–429, 2015.
- [52] Chien-Ju Ho, Aleksandrs Slivkins, Siddharth Suri, and Jennifer Wortman Vaughan. Incentivizing high quality crowdwork. In *24th Intl. World Wide Web Conf. (WWW)*, 2015.
- [53] Chien-Ju Ho, Rafael Frongillo, and Yiling Chen. Eliciting categorical data for optimal aggregation. In *30th Advances in Neural Information Processing Systems (NIPS)*, 2016.
- [54] Chien-Ju Ho, Aleksandrs Slivkins, and Jennifer Wortman Vaughan. Adaptive contract design for crowdsourcing markets: Bandit algorithms for repeated principal-agent problems. *Journal of Artificial Intelligence Research*, 55:317 – 359, 2016.
- [55] Kevin Anthony Hoff and Masooda Bashir. Trust in automation: Integrating empirical evidence on factors that influence trust. *Human factors*, 57(3):407–434, 2015.
- [56] Yasuo Ishihara and Steve Johnson. Aircraft systems and methods for managing runway awareness and advisory system (raas) callouts, February 12 2019. US Patent 10,204,523.
- [57] Leslie Pack Kaelbling, Michael L Littman, and Andrew W Moore. Reinforcement learning: A survey. *Journal of artificial intelligence research*, 4:237–285, 1996.
- [58] Daniel Kahneman and Amos Tversky. Prospect theory: An analysis of decisions under risk. *Econometrica*, pages 263–291, 1979.
- [59] Daniel Kahneman and Amos Tversky. Prospect theory: An analysis of decision under risk. In *Handbook of the fundamentals of financial decision making: Part I*, pages 99–127. World Scientific, 2013.
- [60] Daniel Kahneman, Stewart Paul Slovic, Paul Slovic, and Amos Tversky. *Judgment under uncertainty: Heuristics and biases*. Cambridge university press, 1982.
- [61] Daniel Kahneman, Jack L Knetsch, and Richard H Thaler. The endowment effect, loss aversion, and status quo bias. *The Journal of Economic Perspectives*, 5(1):193–206, 1991.
- [62] Emir Kamenica and Matthew Gentzkow. Bayesian persuasion. *American Economic Review*, 101(6): 2590–2615, 2011.
- [63] Niklas Karlsson, George Loewenstein, and Duane Seppi. The ostrich effect: Selective attention to information. *Journal of Risk and uncertainty*, 38:95–115, 2009.

- [64] Harmanpreet Kaur, Harsha Nori, Samuel Jenkins, Rich Caruana, Hanna Wallach, and Jennifer Wortman Vaughan. Interpreting interpretability: Understanding data scientists’ use of interpretability tools for machine learning. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, pages 1–14, 2020.
- [65] Joshua Klayman and Young-Won Ha. Confirmation, disconfirmation, and information in hypothesis testing. *Psychological review*, 94(2):211, 1987.
- [66] Jon Kleinberg and Manish Raghavan. How do classifiers induce agents to invest effort strategically? In *Proceedings of the 2019 ACM Conference on Economics and Computation*, pages 825–844, 2019.
- [67] Amanda Kube, Sanmay Das, and Patrick J Fowler. Allocating interventions based on predicted outcomes: A case study on homelessness services. In *Proceedings of the AAAI Conference on Artificial Intelligence*, volume 33, pages 622–629, 2019.
- [68] Amanda Kube, Sanmay Das, Patrick J Fowler, and Yevgeniy Vorobeychik. Just resource allocation? how algorithmic predictions and human notions of justice interact. In *Proceedings of the 23rd ACM Conference on Economics and Computation*, pages 1184–1242, 2022.
- [69] Amanda R Kube, Sanmay Das, and Patrick J Fowler. Community-and data-driven homelessness prevention and service delivery: optimizing for equity. *Journal of the American Medical Informatics Association*, 30(6):1032–1041, 2023.
- [70] Tze Leung Lai and Herbert Robbins. Asymptotically efficient adaptive allocations rules. *Advances in Applied Mathematics*, 6:4–22, 1985.
- [71] Wouter Kool Lauren Treiman, Chien-Ju Ho. Humans forgo reward to instill fairness into AI. Working paper, 2023.
- [72] Zhuoshu Li, Kelsey Lieberman, William Macke, Sofia Carrillo, Chien-Ju Ho, Jason Wellen, and Sanmay Das. Incorporating compatible pairs in kidney exchange: A dynamic weighted matching model. In *Proceedings of the 2019 ACM Conference on Economics and Computation (EC)*, 2019.
- [73] Q Vera Liao and Jennifer Wortman Vaughan. Ai transparency in the age of llms: A human-centered research roadmap. *arXiv preprint arXiv:2306.01941*, 2023.
- [74] Timothy P Lillicrap, Jonathan J Hunt, Alexander Pritzel, Nicolas Heess, Tom Erez, Yuval Tassa, David Silver, and Daan Wierstra. Continuous control with deep reinforcement learning. *arXiv preprint arXiv:1509.02971*, 2015.
- [75] Han Liu, Vivian Lai, and Chenhao Tan. Understanding the effect of out-of-distribution examples and interactive explanations on human-ai decision making. *Proceedings of the ACM on Human-Computer Interaction*, 5(CSCW2):1–45, 2021.
- [76] Yang Liu and Chien-Ju Ho. Incentivizing high quality user contributions: New arm generation in bandit learning. In *32nd AAAI Conference on Artificial Intelligence (AAAI)*, 2018.
- [77] Zhuoran Lu and Ming Yin. Human reliance on machine learning models when performance feedback is limited: Heuristics and risks. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*, pages 1–16, 2021.
- [78] Scott M Lundberg and Su-In Lee. A unified approach to interpreting model predictions. In *Advances in Neural Information Processing Systems*, 2017.

- [79] Vinayak Mathur, Yannis Stavarakas, and Sanjay Singh. Intelligence analysis of tay twitter bot. In *2016 2nd International Conference on Contemporary Computing and Informatics (IC3I)*, pages 231–236. IEEE, 2016.
- [80] Daniel McFadden. Econometric models of probabilistic choice. *Structural analysis of discrete data with econometric applications*, 198272, 1981.
- [81] Volodymyr Mnih, Koray Kavukcuoglu, David Silver, Alex Graves, Ioannis Antonoglou, Daan Wierstra, and Martin Riedmiller. Playing atari with deep reinforcement learning. *arXiv preprint arXiv:1312.5602*, 2013.
- [82] Volodymyr Mnih, Koray Kavukcuoglu, David Silver, Andrei A Rusu, Joel Veness, Marc G Bellemare, Alex Graves, Martin Riedmiller, Andreas K Fidjeland, Georg Ostrovski, et al. Human-level control through deep reinforcement learning. *Nature*, 518(7540):529, 2015.
- [83] Saumik Narayanan, Kassa Korley, Chien-Ju Ho, and Siddhartha Sen. Improving the strength of human-like models in chess. In *Human in the Loop Learning (HiLL) Workshop at NeurIPS*, 2022.
- [84] Saumik Narayanan, Guanghui Yu, Wei Tang, Chien-Ju Ho, and Ming Yin. How does predictive information affect human ethical preferences? In *ACM Conference on AI, Ethics, and Society*, 2022.
- [85] Saumik Narayanan, Guanghui Yu, Chien-Ju Ho, and Ming Yin. How does value similarity affect human reliance in ai-assisted ethical decision making? In *ACM Conference on AI, Ethics, and Society*, 2023.
- [86] Nagarajan Natarajan, Inderjit S Dhillon, Pradeep K Ravikumar, and Ambuj Tewari. Learning with noisy labels. *Advances in neural information processing systems*, 26, 2013.
- [87] Andrew Y Ng, Stuart J Russell, et al. Algorithms for inverse reinforcement learning. In *International Conference on Machine Learning*, 2000.
- [88] Raymond S Nickerson. Confirmation bias: A ubiquitous phenomenon in many guises. *Review of general psychology*, 2(2):175–220, 1998.
- [89] Martin A Nowak, Karen M Page, and Karl Sigmund. Fairness versus reason in the ultimatum game. *Science*, 289(5485):1773–1775, 2000.
- [90] Ziad Obermeyer, Brian Powers, Christine Vogeli, and Sendhil Mullainathan. Dissecting racial bias in an algorithm used to manage the health of populations. *Science*, 366(6464):447–453, 2019.
- [91] Shutai Okamura, Takeshi Hatakeyama, Takahiro Yamaguchi, and Tsutomu Uenoyama. Radar detection system and radar detection method, January 19 2021. US Patent 10,895,638.
- [92] Eli Pariser. *The filter bubble: How the new personalized web is changing what we read and how we think*. Penguin, 2011.
- [93] Neehar Peri, Michael Curry, Samuel Dooley, and John Dickerson. Preferencenet: Encoding human preferences in auction design with deep learning. *Advances in Neural Information Processing Systems*, 34:17532–17542, 2021.
- [94] Joseph T Pesik and David Matty. Determination of collision risks between a taxiing aircraft and objects external to the taxiing aircraft, February 4 2020. US Patent 10,553,123.

- [95] Forough Poursabzi-Sangdeh, Daniel G Goldstein, Jake M Hofman, Jennifer Wortman Wortman Vaughan, and Hanna Wallach. Manipulating and measuring model interpretability. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*, pages 1–52, 2021.
- [96] Walter Quattrociocchi, Antonio Scala, and Cass R Sunstein. Echo chambers on facebook. *Available at SSRN 2795110*, 2016.
- [97] Matthew Rabin and Ted O’Donoghue. Doing It Now or Later. *American Economic Review*, 1999.
- [98] Jack W Rae, Sebastian Borgeaud, Trevor Cai, Katie Millican, Jordan Hoffmann, Francis Song, John Aslanides, Sarah Henderson, Roman Ring, Susannah Young, et al. Scaling language models: Methods, analysis & insights from training gopher. *arXiv preprint arXiv:2112.11446*, 2021.
- [99] Manish Raghavan, Aleksandrs Slivkins, Jennifer Vaughan Wortman, and Zhiwei Steven Wu. The externalities of exploration and how data diversity helps exploitation. In *Conference on Learning Theory*, pages 1724–1738. PMLR, 2018.
- [100] Deepak Ramachandran and Eyal Amir. Bayesian inverse reinforcement learning. In *IJCAI*, volume 7, pages 2586–2591, 2007.
- [101] Kamalini Ramdas, Khaled Saleh, Steven Stern, and Haiyan Liu. Variety and experience: Learning and forgetting in the use of surgical devices. *Management Science*, 64(6):2590–2608, 2018.
- [102] Gonzalo Ramos, Jina Suh, Soroush Ghorashi, Christopher Meek, Richard Banks, Saleema Amer-shi, Rebecca Fiebrink, Alison Smith-Renner, and Gagan Bansal. Emerging perspectives in human-centered machine learning. In *Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems*, pages 1–8, 2019.
- [103] Charvi Rastogi, Yunfeng Zhang, Dennis Wei, Kush R Varshney, Amit Dhurandhar, and Richard Tomsett. Deciding fast and slow: The role of cognitive biases in ai-assisted decision-making. *Proceedings of the ACM on Human-Computer Interaction*, 6(CSCW1):1–22, 2022.
- [104] Vikas Raykar, Shipeng Yu, Linda Zhao, Gerardo Valadez, Charles Florin, Luca Bogoni, and Linda Moy. Learning from crowds. *Journal of Machine Learning Research*, 11:1297–1322, 2010.
- [105] Amy Rechkemmer and Ming Yin. When confidence meets accuracy: Exploring the effects of multiple performance indicators on trust in machine learning models. In *CHI Conference on Human Factors in Computing Systems*, pages 1–14, 2022.
- [106] Marco Tulio Ribeiro, Sameer Singh, and Carlos Guestrin. " why should i trust you?" explaining the predictions of any classifier. In *Proceedings of the 22nd ACM SIGKDD international conference on knowledge discovery and data mining*, pages 1135–1144, 2016.
- [107] Herbert Robbins and Sutton Monro. A stochastic approximation method. *The annals of mathematical statistics*, pages 400–407, 1951.
- [108] Kristin E Schaefer, Jessie YC Chen, James L Szalma, and Peter A Hancock. A meta-analysis of factors influencing the development of trust in automation: Implications for understanding autonomy in future systems. *Human factors*, 58(3):377–400, 2016.
- [109] Clayton Scott. A rate of convergence for mixture proportion estimation, with application to learning from noisy labels. In *Artificial Intelligence and Statistics*, pages 838–846. PMLR, 2015.

- [110] Marybeth Shinn, Andrew L Greer, Jay Bainbridge, Jonathan Kwon, and Sara Zuiderveen. Efficient targeting of homelessness prevention services for families. *American journal of public health*, 103 (S2):S324–S330, 2013.
- [111] David Silver, Thomas Hubert, Julian Schrittwieser, Ioannis Antonoglou, Matthew Lai, Arthur Guez, Marc Lanctot, Laurent Sifre, Dhharshan Kumaran, Thore Graepel, et al. A general reinforcement learning algorithm that masters chess, shogi, and go through self-play. *Science*, 362(6419):1140–1144, 2018.
- [112] Abneesh Singla, Srinivas D Gonabal, Pradeep Huncha, Vedavyas Rallabandi, Jaibir Singh, Sunil Kumar KS, et al. System and method for monitoring compliance with air traffic control instructions, August 25 2020. US Patent 10,755,583.
- [113] Kenneth A Small. A discrete choice model for ordered alternatives. *Econometrica: Journal of the Econometric Society*, pages 409–424, 1987.
- [114] Hummy Song, Anita L Tucker, Karen L Murrell, and David R Vinson. Closing the productivity gap: Improving worker productivity through public relative performance feedback and validation of best practices. *Management Science*, 64(6):2628–2649, 2018.
- [115] Petru Soviany, Radu Tudor Ionescu, Paolo Rota, and Nicu Sebe. Curriculum learning: A survey. *International Journal of Computer Vision*, 130(6):1526–1565, 2022.
- [116] Zhe Sun, Cheng Zhang, Pingbo Tang, Yuhao Wang, and Yongming Liu. Bayesian network modeling of airport runway incursion occurring processes for predictive accident control. In *Advances in Informatics and Computing in Civil and Construction Engineering: Proceedings of the 35th CIB W78 2018 Conference: IT in Design, Construction, and Management*, pages 669–676. Springer, 2019.
- [117] Richard S. Sutton and Andrew G. Barto. *Reinforcement Learning: An Introduction*. The MIT Press, second edition, 2018.
- [118] Wei Tang and Chien-Ju Ho. Bandit learning with biased human feedback. In *Proceedings of the 18th International Conference on Autonomous Agents and Multi-Agent Systems (AAMAS)*, pages 1324–1332, 2019.
- [119] Wei Tang and Chien-Ju Ho. On the bayesian rational assumption in information design. In *Proceedings of the AAAI Conference on Human Computation and Crowdsourcing*, volume 9, pages 120–130, 2021.
- [120] Wei Tang, Ming Yin, and Chien-Ju Ho. Leveraging peer communication to enhance crowdsourcing. In *The World Wide Web Conference*, pages 1794–1805. ACM, 2019.
- [121] Wei Tang, Chien-Ju Ho, and Yang Liu. Differentially private contextual dynamic pricing. In *Proceedings of the 19th International Conference on Autonomous Agents and Multi-Agent Systems (AAMAS)*, 2020.
- [122] Wei Tang, Chien-Ju Ho, and Yang Liu. Bandit learning with delayed impact of actions. *Advances in Neural Information Processing Systems*, 34:26804–26817, 2021.
- [123] Wei Tang, Chien-Ju Ho, and Yang Liu. Linear models are robust optimal under strategic behavior. In *International Conference on Artificial Intelligence and Statistics*, pages 2584–2592. PMLR, 2021.

- [124] Eric J Topol. High-performance medicine: the convergence of human and artificial intelligence. *Nature medicine*, 25(1):44–56, 2019.
- [125] Kenneth E Train. *Discrete choice methods with simulation*. Cambridge university press, 2009.
- [126] Long Tran-Thanh, Archie Chapman, Enrique Munoz De Cote, Alex Rogers, and Nicholas R Jennings. Epsilon–first policies for budget–limited multi-armed bandits. In *Proceedings of the AAAI Conference on Artificial Intelligence*, volume 24, pages 1211–1216, 2010.
- [127] Amos Tversky and Daniel Kahneman. Belief in the law of small numbers. *Psychological bulletin*, 76(2):105, 1971.
- [128] Amos Tversky and Daniel Kahneman. Judgment under uncertainty: Heuristics and biases: Biases in judgments reveal some heuristics of thinking under uncertainty. *science*, 185(4157):1124–1131, 1974.
- [129] Amos Tversky and Daniel Kahneman. The framing of decisions and the psychology of choice. *Science*, 211(4481):453–458, 1981.
- [130] Oleksandra Vereschak, Gilles Bailly, and Baptiste Caramiaux. How to evaluate trust in ai-assisted decision making? a survey of empirical methodologies. *Proceedings of the ACM on Human-Computer Interaction*, 5(CSCW2):1–39, 2021.
- [131] John von Neumann and Oscar Morgenstern. *Theory of Games and Economic Behavior*. Princeton University Press, 1944.
- [132] Xin Wang, Yudong Chen, and Wenwu Zhu. A survey on curriculum learning. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 44(9):4555–4576, 2021.
- [133] Christopher J.C.H. Watkins and Peter Dayan. Q-learning. *Machine learning*, 8(3-4):279–292, 1992.
- [134] Christabel Wayllace, Sunwoo Ha, Yuchen Han, Jiaming Hu, Shayan Monadjemi, William Yeoh, and Alvitta Ottley. Dragon-v: detection and recognition of airplane goals with navigational visualization. In *Proceedings of the AAAI Conference on Artificial Intelligence*, volume 34, pages 13642–13643, 2020.
- [135] Jacob Whitehill, Ting fan Wu, Jacob Bergsma, Javier R. Movellan, and Paul L. Ruvolo. Whose vote should count more: Optimal integration of labels from labelers of unknown expertise. In *Advances in Neural Information Processing Systems (NIPS)*, 2009.
- [136] Marty J Wolf, K Miller, and Frances S Grodzinsky. Why we should have seen that coming: comments on microsoft’s tay" experiment," and wider implications. *Acm Sigcas Computers and Society*, 47(3): 54–64, 2017.
- [137] Ming Yin, Jennifer Wortman Vaughan, and Hanna Wallach. Understanding the effect of accuracy on trust in machine learning models. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, page 279. ACM, 2019.
- [138] Guanghui Yu and Chien-Ju Ho. Environment design for biased decision makers. In *Proceedings of the International Joint Conference on Artificial Intelligence (IJCAI)*, 2022.
- [139] Kaiqing Zhang, Zhuoran Yang, and Tamer Başar. Multi-agent reinforcement learning: A selective overview of theories and algorithms. *Handbook of reinforcement learning and control*, pages 321–384, 2021.

- [140] Yunfeng Zhang, Q Vera Liao, and Rachel KE Bellamy. Effect of confidence and explanation on accuracy and trust calibration in ai-assisted decision making. In *Proceedings of the 2020 Conference on Fairness, Accountability, and Transparency*, pages 295–305, 2020.
- [141] Yudian Zheng, Guoliang Li, Yuanbing Li, Caihua Shan, and Reynold Cheng. Truth inference in crowdsourcing: Is the problem solved? *Proceedings of the VLDB Endowment*, 10(5):541–552, 2017.
- [142] Brian D Ziebart, Andrew Maas, J Andrew Bagnell, and Anind K Dey. Maximum entropy inverse reinforcement learning. In *Proceedings of the AAAI Conference on Artificial Intelligence*, 2008.