

Social Media Algorithms versus Preferences in a large-scale RCT

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Abstract

Is engagement with harmful social media content driven by algorithmically curated feeds or user tastes? I conduct an RCT replacing personalization algorithms with random content delivery for over one million users of a prominent TikTok-like platform in India. I find a trade-off: random post recommendation lowers exposure to anti-minority ('toxic') content by 8.7% on average, and also lowers platform usage. The intervention's impact on socially undesirable behaviors was blunted as users greatly valued posts that the recommendation algorithm did not show them. Strikingly, the proportion of toxic posts shared increased by 7.8%. An economic model incorporating heterogeneous user preferences, endogenous social media activity, and an engagement maximizing algorithm, rationalizes these results and quantifies malleability in user behavior. Estimated behavioral parameters reveal that the influence of exposure to diversified feeds is low, but users are not entirely mechanical in sharing the content they are fed. This points towards limited effectiveness of regulatory measures targeting algorithms that impose substantial costs in terms of user activity on the platform.

Keywords: Digital Economies, Technology Policy, Development, RCT, Machine Learning

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1 Introduction

The pervasive influence of social media, with users spending an average of 151 minutes daily on these platforms, has intensified scrutiny of their adverse impacts (Allcott et al., 2020; Braghieri et al., 2022). From deteriorating mental health outcomes to increased political polarization, a range of concerns has emerged. These issues are hypothesized to be exacerbated by personalized content delivery systems that reduce search costs for belief-confirming information (Girimella and Eckles, 2017; Tucker et al., 2018). Designed to maximize user engagement through tailored content recommendations, these feed-ranking algorithms are thought to create 'filter bubbles' that deepen political divisions (Guess et al., 2023a). The potential consequences extend beyond online interactions, with recent studies linking extreme 'toxic' content with increased offline violence (Bursztyn et al., 2019; Müller and Schwarz, 2021).¹

In response to these concerns, various government bodies, including the US Senate and the Supreme Court, are actively discussing regulations targeting algorithms.² While these regulations are expected to yield benefits by reducing users' exposure to hateful posts, they may also impose substantial costs on platforms. Moreover, the feedback loop between consumer behaviors and algorithms may limit the effectiveness of policies aimed at minimizing socially undesirable engagement, especially if users aren't easily influenced by new information they are exposed to (HosseiniMardi et al., 2024). Despite the significant behavioral implications of regulating algorithms, there is little experimental evidence on the role of user preferences or the malleability of human behavior in determining engagement with extreme posts when algorithmic content curation is disabled.

This paper addresses this gap by examining a year-long experiment I conducted, in collaboration with a prominent social media platform in India. The experiment temporarily disabled personalization algorithms for over a million users. The analysis is structured along three key research questions. First, what is the cost of regulating personalization algorithms for social media platforms? The cost to firms is measured by reduced number of daily active users, and the consequent loss in advertising revenue. Second, does exposing biased users to more diverse feeds reduce the spread of harmful content? In other words, is socially undesirable behavior driven by mechanical consumption of the feed? Third, how malleable is user behavior when exposed to automatically personalized social media feeds? Alternatively, to what extent are socially undesirable behaviors, such as sharing posts that are hurtful towards minority groups, reinforced by exposure to toxic content via recommendation algorithms?³ A rich literature in economics has characterized the demand for traditional

¹Toxicity of a post is a measure of its harmfulness, or the harm it can cause, and is defined as per Google's Perspective API. Perspective is a free API that uses machine learning to identify 'toxic' comments, where toxicity is defined as "rude, disrespectful, or unreasonable comment that is likely to make someone leave a discussion." Perspective has been adopted by organizations like The New York Times to automatically regulate and filter abusive comments, and has also been used in academic research (Jiménez Durán, 2022). See <https://perspectiveapi.com/how-it-works/> and <https://perspectiveapi.com/case-studies/>, for a comprehensive guide and applications of this API.

²The regulatory policies targeting algorithms that are being considered in the US are expected to impact close to 300 million social media users. See <https://shorturl.at/WKWPu> for minutes of the Subcommittee on Privacy, Technology, and the Law convened under the US Senate Committee on the Judiciary. See also <https://shorturl.at/G6Lj4> for SCOTUS view on Texas, Florida regulation of social media moderation.

³Here, sharing particularly means sharing posts off the platform, to other social media platforms like

media content, and the effects of biased media exposure on economic, social and political behaviors (See (DellaVigna and La Ferrara, 2015) for a comprehensive review). However, the findings of this literature cannot be generalized because unlike broadcast media, social media platforms customize information that each user is exposed to.

I bring experimental evidence from a TikTok-like Indian social media platform, with close to 200 million monthly active users (henceforth called SM), to answer these questions. My field intervention effectively ‘switched off’ the personalization algorithm for close to a million treated users, and exposed them to randomly picked content instead. Therefore, treatment was randomly assigned to 0.5% of SM’s users, and exposure to content in the treatment group was given purely by chance. This enabled the identification of demand (user preferences) and supply (algorithms) factors that drive online misinformation. In particular, I study engagement with harmful anti-minority (or toxic) content when the treatment reduces exposure to such content for some users.

The personalization algorithm for control users continued to optimize over various metrics of user satisfaction during the intervention period. SM’s typical algorithm, like that of Netflix, does this by ranking the kind of content a user has engaged with in the past. These rank-orderings place a higher ‘score’ on posts that the user is more likely to ‘share’, where the likelihood of engagement is estimated using machine learning models trained on a recent history of user behavior.⁴ The intervention replaced these ranked lists of posts (henceforth called content feeds) with random draws of content, for each treated user, on each day.

I find a trade-off: random post recommendation lowers exposure to anti-minority (‘toxic’) content, but also lowers usage of the platform by 14.4%. Treated users viewed and shared fewer posts of any variety, and reduced the time spent on the application by 35.2%. Therefore, I show that regulating algorithms is expensive for platforms, and quantify the costs of this intervention, in order to answer the first research question.

Second, the treatment reduced the number of toxic posts viewed and shared on average, by 27% and 19%, respectively. That is to say, not only did the treatment reduce the total number of posts shared, it also decreased the absolute quantity of toxic content shared by the average user. However, this led to a 7.8% *increase* in the proportion of toxic posts shared, as the decrease in toxic shares was smaller than the decrease in total shares.

These results indicate that users receive greater value from sharing toxic content when they encounter fewer toxic posts during the intervention. Upon being treated, they view and share fewer toxic posts, but the reduction in toxic posts shared is smaller (in absolute terms) than the effect on the number of toxic posts viewed and the total number of posts shared. This suggests that users actively seek out posts aligning with their tastes, even when such content is not readily served to them via the personalization algorithm. I also provide complimentary evidence that treated users were more likely to use the ‘search’ feature on

WhatsApp.

⁴This is operationalized through contextual embeddings that are obtained by factorizing engagement matrices constructed at the user-post level (Athey and Imbens, 2019), as is delineated in greater detail later. The intervention was administered using algorithmically generated latent feature vectors for each user, called embedding vectors, by factorizing an engagement matrix containing all users and posts. These embedding vectors represent some abstract measure of user tastes over social media content as learned by the personalization algorithm.

the platform.⁵

I rationalize these results, and estimate malleability in user behavior, with a simple economic model in which (1) engagement is endogenous, (2) users' sharing behavior reflects a balance between their intrinsic preferences for sharing toxic content and the composition of their feeds, and (3) the status quo algorithm serves to maximize engagement. The model enables characterization of heterogeneous responses to the intervention, so that the overall increase in the *proportion* of shares that are toxic is driven by users with lower proclivity towards toxic content.

The model supports the claim that the reduction in the *number* of toxic posts shared comes from users with a high preference for toxic content, in major part due to their reduced engagement with the platform. This is because the median treated user is exposed to fewer toxic posts (by design), but also shares fewer posts overall. As a result, the average treated user shares a higher proportion of toxic posts, even as she was exposed to fewer such posts.

Using the model to structure an analysis of the data, I find an elasticity of toxic sharing with respect to toxic viewing of only 0.16. This means that user behavior is not malleable in the short run, when exposed to random content for a period of one month. The implication is that users minimally update their view of the range of ideas that are acceptable in public discourse, which they learn from the automatically generated content feeds.⁶ Therefore, user behavior is largely driven by pre-existing user tastes, and the intervention has a limited effect on user behavior.

These results have a number of important policy implications for regulating digital technologies to minimize harm and political polarization, especially in developing countries. Technology policy would be highly cost-effective if the benefits of any intervention that reduced exposure to toxic content were bolstered by the influence of diverse content on behavior in a way that breaks existing feedback loops between algorithms and users, or even generating positive feedback loops. I show that while the intervention significantly reduces the proportion of toxic content viewed, a large proportion of new behaviors can be predicted using engagement patterns at baseline, and not the exposure to new information. Therefore, any intervention that reduces toxic exposure may not be entirely effective in changing user behavior, because the benefits of behavior change are very limited, at best. This suggests a multipronged approach to making digital spaces less hostile.

1.1 Related Literature

This paper contributes to three strands of the literature. First, it closely relates to the literature on implications of new communication technologies on human behavior and wel-

⁵The search feature resembles any search engine, where users can type in keywords to find posts that are relevant to their interests.

⁶The range of ideas that are considered acceptable in public discourse is popularly known as the Overton Window (Astor, 2019). The Overton Window essentially informs people about the social norms, about what is considered acceptable to say in public. Matthew Desmond (2023) provides an insightful definition in his book *Poverty, by America*, relayed to him by psychologist Betsy Levy Paluck, ‘‘Norms license us to do things we already believe in’’ (Ch 8, pp 131). Here, the idea is that users learn what is okay to say in public by observing the content that is recommended to them by the algorithm. I provide survey evidence to validate this assumption in Section 5.

fare.⁷ This includes the contributions of Nyhan et al. (2023), Guess et al. (2023a) and Guess et al. (2023b), where a team of social scientists collaborated with Meta (henceforth called, the Meta-Science studies), to experimentally study the role of their feed-ranking algorithms in driving political polarization in the run-up to the 2020 US Presidential Elections. This paper, similar to the Meta-Science studies, analyzes data from an *on-platform* experiment. These studies found no differences in measures of affective polarization, measured using surveys that users were asked to opt into. The main findings are consistent with my results, as users who were served lower amounts of toxic content, do not seem to change their behavior in the short-run.

My experiment complements this work in the following ways. **(1)** I analyze outcomes from the platform's administrative data, instead of relying on survey responses. This makes the analysis less prone to experimenter demand and Hawthorne effects. **(2)** The experiments above study fairly short-term effects of disrupting the usual algorithm, while this experiment lasted for 11 months. In future work, I will study the long-term effects of the intervention on user behavior, as these data have also been secured. **(3)** My work adds breadth to the existing research as I analyze preferences revealed 'in the wild' through high-frequency engagement behavior of users with millions of posts on SM, in a developing country with a vastly different political context (See section 2 for more details). India, despite being the second largest market for digital platforms, has been scarcely studied in terms of interactions with evolving technologies. I also collect survey data for a large subset of control and treated users, to complement the analysis of affective polarization, and mental health outcomes in this literature.⁸

Second, this paper relates to a rich literature studying the relationship between media bias and political polarization (DellaVigna and Kaplan, 2007; Gentzkow and Shapiro, 2011; Chiang and Knight, 2011). Even though social media differs from traditional media in some key aspects (most notably, entry costs for content creators, and personalization of content), existing literature sheds light on how exposure to content (supply factors) changes important aspects of human behavior (Jensen and Oster, 2009). Similarly, this literature provides a framework to understand the demand for slanted content (slanted news in particular, for example Martin and Yurukoglu (2017)).

This paper contributes to the media-bias literature by analyzing demand for shaded information, when the supply of information is itself endogenously determined by a person-

⁷The literature in economics has emphasized the effect of technology on 'offline' measures of welfare like protest participation (Enikolopov et al., 2020; Manacorda and Tesei, 2020; Enikolopov et al., 2018; Cantoni et al., 2023), voting behavior (Zhuravskaya et al., 2020; Gonzalez, 2021; Fujiwara et al., 2023), mental health outcomes (Allcott et al., 2020; Braghieri et al., 2022), and targeted attacks on vulnerable communities by non-state actors (Bursztyn et al., 2019; Müller and Schwarz, 2021). However, the behavioral responses in many studies using observational data from social media platforms may be confounded by the algorithm itself.

⁸While the offline effects on online engagement are important and have been widely studied, there is a growing recognition that time spent online itself has a profound impact on human welfare. Consequently, there is a growing interest in questions related with mobile phone usage (Björkegren, 2019), mobile money (Suri and Jack, 2016), digital addiction (Allcott et al., 2022; Aridor, 2022), online advertising (Goldfarb and Tucker, 2011; Brynjolfsson et al., 2024), biased news consumption (Levy, 2021), spread of misinformation (Acemoglu et al., 2021), radicalization (Hosseini Mardi et al., 2020), and employment of surveillance technologies (Beraja et al., 2023b,a). Recent work has also questioned social media's role in engagement with hate speech, making policy recommendations to check the spread of harmful posts (Jiménez Durán, 2022).

alization algorithm. Prior work has asserted that changing social norms are key in driving behavioral responses to biased information (Bursztyn et al., 2020). I build a structural model on a similar vein, where social media engagement is driven by utility derived from social-image concerns, while conforming to norms practiced in one’s identity-based network (Akerlof and Kranton, 2000; Butera et al., 2022). However, direct evidence on the mechanisms driving behavioral responses due to (social) media bias is scarce, especially on TikTok-like platforms that currently attracts a majority proportion of social media users, and the younger demographic, in particular (Aridor et al., 2024).

Finally, I contribute to a burgeoning literature on the economics of artificial intelligence and algorithms (Acemoglu, 2021). Fairness concerns notwithstanding, there is a growing interest in the impact of black-box algorithms in a world where they have a wide variety of applications (Rambachan et al., 2020). Examples of such human-computer interactions include online shopping for given personalized information, decision-making in the legal system, and hiring in the labor market (Goldfarb and Tucker, 2019). Notably, these human-computer interactions are especially important to study in the presence of behavioral responses that may generate substantial unanticipated effects (Björkegren et al., 2020; Kleinberg et al., 2022; Agan et al., 2023).

I analyze the effect of algorithms (or their absence, thereof) in a context where these technologies have been introduced only recently. This is important as more and more people interact with technologies that generate customized feeds using different types of machine learning algorithms, in contexts with scant regulations. My work shows that while social media platforms aggressively use costly algorithms to retain users on the platform, users are active agents who often seek out the content that aligns with their pre-existing biases (HosseiniMardi et al., 2024). This is crucial because it is not clear if behavioral responses dampen or bolster the effects of regulatory policies that target algorithms.

The remaining paper is organized as follows. Sections 2 provide background details of the context and the administrative data employed in this study. Section 3 delineates the design of the experiment, and provides descriptive statistics that motivate an interrogation of mechanisms with a structural model. Section 5 provides a simple theoretical framework that generates testable hypotheses to structure the empirical analysis. This structural model also provides an estimation strategy to measure the behavioral effect of content exposure.

2 Background and Data

I lay out the context of this study to highlight the importance of behavioral responses to viewing social media posts, in the presence of new digital technologies. I use high frequency administrative data on exposure to and engagement with posts by millions of SM users. I also use various methods in Machine Learning and Text Analysis to classify 15 million multilingual posts that were ‘viewed’ and ‘shared’ by my sample of users. This was done in order to understand the behavioral factors driving engagement with extreme content, as being distinct from the supply factors, like the algorithmic recommendations. These behavioral responses, in turn, determine content exposure, as feed curation technologies attempt to learn ‘preferences’ from human behavior, and could lead to harmful downstream consequences, like rabbit holes of (mis)information and radicalizing content.

2.1 Social Media in India

There has been a sharp increase in political polarization and hate speech on social media platforms around the world (Boxell et al., 2022). Facebook whistleblower, Frances Haugen, has alleged that the company's personalization algorithms promote extreme content (Haugen, 2021). She also leaked the company's internal documents show that the company is aware of the harms that have been caused, not just in the US, but also in India ⁹. This has piqued academic interest in the factors that lead to the production and propagation of hateful content on these platforms (Huszár et al., 2022).

With over 500 million social media users, India provides a highly relevant context for studying these questions as social media has grave consequences for the socio-political environment in this setting. India is among the largest markets for online platforms in the world, second only to China.¹⁰ Social media usage has proven to be very harmful in the Indian setting, because various posts are known to have provoked instances of violence, in the form of mob lynchings, riots, and hate crimes (Banaji et al., 2019). Details of the particular challenges faced by social media platforms in India are provided in Appendix D.

Threats to minority communities, stemming from social media usage in India, are speculated to be bolstered by content recommendation algorithms, which are highly sophisticated customization algorithms that employ machine learning or deep learning technologies. This is because, in optimizing content engagement, social media is predicted to generate political filter bubbles or echo chambers (Sunstein, 2001; Conover et al., 2011; Barberá et al., 2015). Such echo chambers are likely to increase user exposure to more extreme and polarized viewpoints in the digital space, possibly leading to radicalization (Gaudette et al., 2021).

2.2 The Platform

I partner with SM, a prominent social media platform in India, to understand the effects of exposure to extreme content, due to content recommendation algorithms. I study how the nature of online interactions changes with my intervention in SM's rich online social network. I assess the contribution of users' existing behavioral patterns in regard to extreme content using SM's data on (close to) 200 million monthly active users.

SM's app features resemble those of TikTok, and the platform made massive gains in market share when TikTok was banned in India due to escalating geo-political tensions with China (Mishra et al., 2022). SM is a content-based social network, meaning that users interact with content rather than with other users, unlike X (formerly, Twitter), where users engage with users they 'follow'. SM's user interface resembles that of Instagram, where users can scroll over content in the form of short videos, images, and text posts. User connectedness with other users is therefore, of little consequence.¹¹

Due to the new (TikTok-like) features this platform offers users, and its multi-lingual interface (with a conspicuous absence of the English language), SM attracts a large propor-

⁹See documents on internally conducted experiments, providing concrete evidence of the problem in India
<https://www.nytimes.com/2021/10/23/technology/facebook-india-misinformation.html>

¹⁰<https://www.statista.com/statistics/278341/number-of-social-network-users-in-selected-countries/>

¹¹Unlike Facebook, where users engage with content from 'Friends,' or from the 'Groups' they join.

tion of young voters among the urban and rural poor in India. This makes such analysis especially important as little is known about political behavior of this demographic in India or about the users of this massive platform (Aridor et al., 2024).

2.3 Control (Current) Algorithm

The estimated treatment effect measures changes in engagement with toxic or non-toxic content for treated users. The control group receives standard algorithmic recommendations generated for each user on the platform, while I intervene on the algorithmic recommendations generated for treated users. In this paper, treatment captures exogenous deviations in recommendations from the current algorithm employed by the platform. I briefly describe the algorithm, to enable an intuitive understanding of the treatment administered in the experiment.

Like Netflix, user feeds on SM are usually customized according to preferences revealed via previous engagement with content using Field Aware Factorization Machines, henceforth called the FFM algorithms (Aggarwal et al., 2016). These Deep Learning models are the most widely used algorithms in the tech industry (Dell, 2024). The algorithm generate a vector of preference weights for each user with respect to some post attributes. This generates a ranking of posts for each user, and users are recommended new posts according to this order, on each day. These vector-weights in the space of some post features are known as embeddings in the machine learning literature (Athey et al., 2021).

The recommender system generates vector weights or embeddings in the space of some (latent) features, where the features could represent a user or post’s likeness to cat videos, or to humorous content, for instance. I provide a general overview of how these algorithms work, along with a simple example, in Appendix E. The workings of the FFM algorithms are useful to understand how the treatment was administered, by replacing algorithmically generated embedding vectors, with randomly chosen ones. I describe the treatment in detail in Section 3, and also simulate a simple FFM algorithm to illustrate the treatment in Appendix E.

2.4 Administrative Platform Data

I use administrative data from the platform to construct my main outcome variables including, viewership of and engagement with polarizing and toxic content at the user level. The administrative data provides information on each post that is viewed or engaged with by any given user. The precise time of exposure and engagement is also recorded in the data, which helps identify distinct patterns in usage according to time of the day and weekends. This allows me to trace the posts a user was exposed to, whether the user chose to engage with the post or not, and under what conditions were the posts engaged with.¹² Consequently, I condition engagement statistics on viewership, which is a feature absent from most observational studies that use social media data (HosseiniMardi et al., 2020).

¹²For instance, Table H.2 shows that treated users were more likely to log onto the platform during the weekend, and in the evenings. This information is insightful for technology policy around questions of platform usage and addiction. The said finding then implies that treated users were most likely spending less time on the platform during the time they could be working, and earning wages.

I also observe user characteristics, like their geographic location, gender, age, date of account creation and language in the administrative data. These static user characteristics, along with users' exposure to and engagement with different types of content during the baseline period allow me to analyze heterogeneous treatment effects. The variables and dimensions of heterogeneity used in this analysis were pre-registered with the AEA RCT Registry (Kalra, 2023). I provide a descriptive summary of user characteristics, as well as engagement at baseline, in Table H.1.

Posts on the platform are also characterized by broad tag genres, user generated hash tags. Further, the text on the images/ videos in the user generated posts is a rich source of information. I adopt various methods to analyze the text data, in order to understand the qualitative nature, tone, and political slant of more than 20 million posts that users engaged with, during the course of the experiment. The descriptive text analysis methods, detailed in Appendix F, highlight the need for contextual embeddings that accurately characterize the potential harm that a post may cause. Next, I use a mix of supervised and unsupervised machine learning methods to construct my main outcome, that is, the toxicity of posts that treated and control users engage with.

2.5 Toxicity Classification

The administrative data provides user-post level data on viewership and engagement, and exceeds 10 TB in size. To measure the main outcome variable, i.e. toxicity of shared posts, I further process the text from images in the post data (using OCR), to classify them as hateful, hurtful, harmful, or toxic. I problematize posts that are a direct threat to the safety of a group or individual, but also posts that are likely to make one leave a discussion.

Multilingual hate speech classification is a key part of my research because I study the impact of my intervention on hatefulness of platform discourse and the content data is in many regional languages (none in English). I use Perspective's machine learning algorithms, developed by Jigsaw at Google, to identify toxicity in the Hindi text extracted from about 20 million posts. Toxic content is defined as “a rude, disrespectful, or unreasonable comment that is likely to make one leave a discussion.”¹³

Perspective provides the best known machine learning solution for toxicity detection, as it relies on transformer based/ deep learning models (most notably, BERT) and training data from millions of comments from different publishers that are annotated by ten human raters on a scale of “very toxic” to “very healthy” contributions (Fortuna et al., 2020). This mix of Supervised and Semi-Supervised Machine Learning methods makes the Perspective algorithm sensitive to context while assigning toxicity scores.¹⁴ Perspective's Machine Learning models are being widely adopted to identify and filter out abusive comments on platforms like New York Times, and are also being frequently used in academic research (Jiménez Durán, 2022; Aridor et al., 2024). These models score a phrase “based on the perceived [negative] impact the text may have in a conversation.”

I construct a binary variable, called ‘toxic,’ which takes value 1 when Perspective's toxicity score on a post is higher than 0.2. I validate this threshold in Appendix F by comparing

¹³<https://perspectiveapi.com/how-it-works/>

¹⁴The source code for the Perspective API is unavailable. These conclusions are drawn from the documentation and the research papers that have used the API.

the performance of this cut-off with other methods of hate speech classification.

3 Experimental Design

I conducted a large-scale and long-term experiment in collaboration with SM, to expose a million users to content that was randomly drawn from the corpus of 2 million posts in the Hindi Language, that is generated each day. This ‘random algorithm’ is contrasted with the usual content feed, which is customized according to user behavior in the past. The experiment enables estimation of demand for toxic content, as being distinct from the supply through the personalization algorithms. The objective of this intervention is to identify the role of personalization algorithms, and the underlying mechanisms, in driving engagement with harmful social media posts.

3.1 Treatment

The control group consists of a random sample of users who were exposed to the usual ranked list of posts. Here, the ranking was determined by user behavior revealed to the algorithm in previous engagements.¹⁵ SM posts, comprising image and video-based posts, are created by star users and influencers on this platform. The intervention does not affect the aggregate supply of content because less than 1% of SM’s users were randomly allocated to the treatment group.¹⁶ Therefore, the intervention left the incentives of the star content creators unaffected.

The random draw of posts for the content feeds of treated users, were generated by replacing the algorithmically generated embedding vectors (as explained in Section 2.3) with randomly picked multidimensional embeddings for each treated user. These ‘random embedding’ vectors generated for treated users were drawn from the distribution of user embeddings that the personalization algorithm generated for control users on each day. That is, for each treated user, the vector of preference weights is just a random draw of numbers. In Appendix E, I show that this effectively randomizes the probability of a post being recommended to a user.

The multidimensional embedding vectors are generated by factorizing engagement matrix at the user-post level, into vectors that characterize both the user and the post in some latent embedding space (Dell, 2024; Athey et al., 2021). For the treatment group on the other hand, embedding vectors are uniformly sampled from an epsilon ball whose centroid is given by the mean embedding in the control group and radius is twice the sum of variances in that vector.¹⁷ In particular, $\boldsymbol{\mu} = \frac{1}{N} \sum_{i=1}^N \mathbf{x}_i$, $\sigma^2 = \frac{1}{N} \sum_{i=1}^N (\mathbf{x}_i - \boldsymbol{\mu})^2$, where \mathbf{x}_i represents the embedding with bias for user i , and N is the total number of users. Formally, for each user embedding, the intervention algorithm uniformly sample a point from an epsilon ball with

¹⁵I do not use data of the remaining 99% control users, because different users may be subject to different AB tests at a given point in time. The random sample of control users is known to be uncontaminated by a different intervention being implemented on the platform during the intervention period.

¹⁶Further, my sample excludes posts that were created more than 60 days before the date that a particular piece of content was served.

¹⁷As per internal company documents and author’s conversations with data science engineers.

the centroid μ as the center and radius $2 \times$ variance of control embeddings.

$$\rho \sim \mathcal{U}(\text{Ball}(\mu, 2\sigma^2))$$

where ρ is the new sampled embedding for the user, and $\mathcal{U}(\text{Ball}(\mu, 2\sigma^2))$ represents a uniform distribution within the epsilon ball centered at μ with radius $2\sigma^2$. This way of administering the intervention has implications for the distribution and ranking of posts in the treatment group.

I demonstrate the key properties of the content distribution in the treatment group by simulating a simple recommender system with two-dimensional embedding vectors in Appendix E. For a randomly generated matrix of engagement for 1,000 control users and 50 posts, I obtain two-dimensional embedding vectors for both the users and the posts using Singular Value Decomposition (Golub and Reinsch, 1971; Wall et al., 2003).¹⁸ In this engagement matrix (R), each row represents a user, and each column represents a post, to generate a sparse matrix, where any entry $r_{ij} \in R$ can be a binary variable indicating whether user i engaged with post j or not. Then I factorize this matrix into its component parts, using an eigenvalue decomposition, $U\Sigma V^T$. Here, U and V^T represent user and post embeddings respectively, so that each column in both these matrices represents an attribute: say, tragedy and comedy. I further build this example, concretely and intuitively, in Figure E.1, and also provide graphical representation of these vectors in the space of two content-types: tragedy (X -axis, dim 1), and comedy (Y -axis, dim 2).

Then, I imitate the procedure or algorithm that implemented the intervention, uniformly at random picking embeddings from a bivariate distribution centered at the mean of the embedding vectors generated for control. This process is then repeated each day for a month-long simulation period, so that the uniformly picked embeddings can converge to a Normal distribution. This is implied by the Central Limit Theorem, as the intervention continues for a longer period of time. In Appendix I, I provide the details of the algorithms used to simulate user embeddings, for both treated and control users.

First, note that the distribution of treatment embeddings, in Figure E.3, approximates a normal distribution centered around the average embedding vector generated by the control group, as would be predicted by the Central Limit Theorem (CLT). Second, the CLT also predicts a smaller spread for the treated embeddings than the control embeddings, because the variance of treated embeddings is divided by the number of treated users.

Finally, and most importantly, the treatment has a greater effect on users with more extreme preferences over dimension 1 of the embedding, or the tragedy of the content. Figure 1 shows that the users with preferences closer to the average user did not see large differences in embedding assignment, and therefore the content feed, when treated. This is an important characteristic of content distribution, and is formally tested using the data on treatment intensity. Figure E.4 shows that the distribution of embedding vectors for treated and control users in the data, is similar to the simulated distribution of embeddings.

¹⁸As a heuristic, I interpret the two dimensions of the embedding vectors as tragedy and comedy, respectively. This means that posts can either be tragic or comic, or some linear combination of these two genres.

3.2 Randomization

Treatment was randomly assigned at the user level to 1% of SM’s user base, which includes both active and inactive users. Users opt-in to be randomly assigned to the treatment for market research and AB tests that are routinely conducted by the platform.¹⁹ The intervention began on February 10, 2023 and continued till the end of the year (December 31, 2023). Administrative and survey data on relevant outcomes was gathered for the baseline period (December, 2022), intervention period (February to December, 2023) and post-intervention period (January-March, 2024).

User IDs were picked randomly at the start of the experiment, and selected users were assigned to the treatment for the entire duration of the intervention. Similarly, control users were also selected at the start of intervention, so that their outcomes were not subject to contamination due to other AB tests/ RCTs running on the platform. For the analysis in this paper, I use a sample of a quarter million *active* users (63041 in the treatment group, and 168773 in the control) who operate the application in Hindi language. A user is said to be active if she viewed at least 200 posts during the baseline period.

I verify the validity of randomization in treatment assignment among the sample of active users by assessing balance in observable user characteristics across treatment and control.²⁰ I consider various observable user characteristics, including gender, state and city of residence, and the week in which a user first created their account. Treatment assignment was also uncorrelated with measures of baseline usage, for example, the total number of posts viewed, or the proportion of toxic posts viewed, during baseline.

Since the treatment was assigned randomly at the user level, I cannot reject the hypothesis that treatment assignment was correlated with user characteristics, either individually or jointly. Table H.1 provides estimates for a randomly selected set of attributes, as the full set of user characteristics is too long for the page.

Table H.1 also provides summary statistics for exposure to and engagement with toxic content at baseline (December, 2022). I am unable to reject the hypothesis that each of these characteristics (individually or jointly) cannot predict treatment assignment. Further, there is balance in behavior at baseline with respect to viewing and sharing all types of posts, including toxic posts, across treated and control users. The randomization procedure was, therefore, validated, as treatment assignment was not correlated with time invariant user attributes like gender, or behavior at baseline, like the fraction of engagement during the weekend or the day time.

It is worth noting, that even though the treatment was randomly assigned, the intensity of the treatment depends on the user’s baseline engagement with toxic content, or their *type*.²¹ For instance, users with higher baseline exposure to toxic content were more likely to face a higher treatment intensity because intervention period embeddings were closer to the mean, while baseline embeddings were further away from the mean. I place both treated and

¹⁹Brown University’s data use agreement does not require additional permissions or consent to be obtained from users, in order to user these data for research purposes.

²⁰The primary test that I performed is represented by the regression, $D_i = \omega_0 + \sum_c \omega_c \mathbf{1}_i(\text{user characteristic} = c) + \varepsilon_i$, where, treatment assignment (D_i) or user characteristics do not vary over time τ .

²¹The relationship between user type and their engagement with toxic content is formally established in Section 5.

control users into different quantiles of toxicity, depending on the percentage of their feed that was toxic at baseline. Therefore, a user is binned with other users who had similar levels of toxic exposure at baseline, and each bin represents user *type* in terms of toxic engagement.

Indeed, Figure 3 shows that the change in exposure to toxic content is positive for users with low baseline exposure to toxic content. As expected, the treatment effect on number of toxic posts viewed is negative for users with high degree of toxic exposure at baseline (Q5 to Q10). Finally, the average treatment effect on toxic exposure in Q4 group cannot be differentiated from zero. Note that this change in toxic exposure is not entirely mechanical. This is because there is a margin of endogenous response in exposure, because the total number of toxic posts viewed also changes.

4 Descriptive Statistics: Five Facts

This paper studies the effect of ‘turning-off’ feed personalization via content recommendation algorithms, on measures of satisfaction and engagement on the platform, as well as on socially undesirable behavior. Treatment effect on measures of overall platform engagement, like total number of posts viewed and time spent, helps identify the value of the algorithm for the customers as well as the cost of the intervention to the platform. Further, the change in the number of toxic posts viewed and shared, helps understand the benefits accrued to society, by way of reduced propagation of harmful content.

Fact 1: The algorithm keeps users engaged online

Since the content recommendations are tailored according to user tastes, any deviation from personalized recommendation is expected to reduce user retention and engagement on the platform. This is because personalization algorithms decrease user’s cost of searching for the content she prefers (Goldfarb and Tucker, 2019). In reducing ease of content discovery, the treatment is thought to reduce overall engagement with the platform. The treatment effects in Table 2 (and Figure G.1) show reduced engagement with the platform, in terms of both the total number of posts viewed and shared.

Table H.2 notes disengagement in all aggregate measures of platform usage. There are negative and statistically significant treatment effects on the number of logins per month (also referred to as retention), the time spent on the platform, as well as the total number of posts viewed. The negative treatment effect on platform engagement is evidenced by the 44% decrease in the shares-to-views ratio. This means that the intervention was costly for the firm, because an average treated user reduced the total time she spent on the platform by 2.5 hours, compared to an average control user, when the average control users spent close to 7 hours per month.²²

Fact 2: Treated users view less toxic content

The objective of this intervention was to understand the role of the customization algorithms in driving socially undesirable behavior, such as online sharing of harmful or toxic content. I

²²The change in time spent is close to 35% of the average time spent by control users.

answer this research question using outcomes such as total number of toxic posts viewed and shared, where toxicity is defined as a binary variable, that takes value 1 when the toxicity score of a post is at least 0.2.²³ The binary outcome variable helps simplify the formal analysis later.

The direction of the treatment effect on the number of toxic posts viewed, for the average user, is unclear a priori. This is because the treatment effect on the number of toxic posts viewed is expected to be positive for users who do not prefer toxic content, but negative for users who do. This is seen in the simulated recommendation algorithms for treatment and control groups in Figure 1, where all treated users are exposed to toxic content with a uniform probability.²⁴ Therefore, the average effect depends on the distribution of user types in the sample, as well as the number of toxic posts in the corpus of posts.

Figure G.1 shows that, during the first month of implementing this intervention (i.e. February 10 to March 10, 2023), the treatment group was exposed to less toxic content, and treated users also shared a lower number of toxic posts in absolute terms. This means that the average user is used to seeing more toxic content if she weren't treated, because random content delivery serves treated users with a lower number of toxic posts. This is demonstrated in Figure 3, where the negative treatment effect on number of toxic posts viewed is largest for users in the highest decile of the user toxicity distribution.

Fact 3: Sharing behavior is sticky

The random exposure to content implies that treated users who saw more toxic content at baseline would now see a lower number of toxic posts. For all such users, I expect to see a reduction in the total number of toxic posts shared because (1) these users have a lower number of toxic posts to share from, and (2) seeing more diverse content may change their otherwise toxic attitudes. However, the average treated user increased the fraction of toxic posts among her shares.

Table 2 shows that while treatment reduced the proportion of toxic posts viewed by 8.7%, but increased the proportion of toxic posts shared by 7.8% percentage points. This is because even though an average SM user saw less toxic posts, and shared a smaller *number* of toxic posts, the average user shared much less of other types of content. Users seem to be inelastic, and tend to seek out content that they prefer, even when the algorithm does not serve it to them readily.

Furthermore, the descriptive statistics indicate that the decrease in toxic shares (19%), is not as large as the decrease in toxic views (26%). This suggests that sharing behavior tends to be sticky.

An Illustration of User Behavior

While the treatment significantly decreased the number of toxic posts viewed by an average user, the reduction in the number of toxic posts shared was not as large. The descriptive evidence points to the fact that user behavior is not malleable, as sharing behavior does not change as much as the views. I illustrate the point using a simple example.

²³See Appendix F for details on criterion to determine the cut-off

²⁴See Appendix E for detailed explanation.

Consider a user who is served 10 posts in a day, and she shares 2 of them. If the user is served 5 toxic posts and 10 non-toxic posts, and she shares 2 toxic and 7 non-toxic posts, then the proportion of toxic posts shared is 22%.

Consider the treated user. Now, the user views 2 toxic posts and 7 non-toxic posts. Suppose, she shares 1 toxic post, but shares only 3 non-toxic posts. Thus, she is disengaged from the platform and shares a total of 4 posts, instead of the 9 she would share if she were not treated. Notice that she also views a smaller number of posts.

This example illustrates that even though the average user views and shares fewer toxic posts upon being treated, there is an increase in the proportion of shares that are toxic. This is because 1 out of 4 shares is toxic under treatment, meaning the proportion of toxic shares is 25%. On the other hand, the proportion of toxic shares is 22% under control. This is true even though the user shared a lower number of toxic posts.

Another useful statistic to build intuition is the elasticity of toxic shares with respect to toxic views. Under the control regime, the user was sharing 2 out of the 5 toxic posts she viewed (40%). However, under the treatment regime, the user shared 1 out of the 2 toxic posts she viewed (50%). Then, her elasticity of toxic shares with respect to toxic views is 0.8.

Fact 4: Treated users search more

Table H.2 shows that treated users were more likely to use the search feature on the platform. I find that the share of time spent online seeking out preferred content is higher for the treated. This complements the evidence on stickiness of sharing behavior, as my measure of shares includes posts accessed both through the trending feed tab, as well as the search tab.

This finding is also consistent with the fact that treated users were more likely to view fewer posts during the intervention period, as my measure of views does not include posts accessed through the search tab. While searching offers an intuitive explanation of the positive effect on fraction of toxic posts shared (despite the negative effect on the proportion of toxic posts viewed), it is less likely to be driving these effects. This is because searched posts constitute 0.01% of viewed posts, and 0.004% of shared posts.

Curiously, the treatment increased the fraction of user activity during the weekends, but reduced daytime usage. This suggests that treated users were more likely to use the platform during their leisure time, and less likely to use it during work hours. Such a finding is especially important for technology policy around questions of platform usage and addiction, as users seem to be spending less time on compulsive engagement due to lack of self-control (Thaler and Shefrin, 1981). This is also consistent with the hypothesis that users seek-out preferred content, as treated users seem to be setting aside leisure time to search for content they like.

Fact 5: Toxic engagement is not driven by selection among stayers

Treatment intensity, in terms of the number of toxic posts viewed, differs by user behavior at baseline. Therefore, reduction in exposure to toxic content is primarily driven by users who saw more toxic content at baseline. The reduction in toxic exposure is not mechanical, due to changes in the total number of posts viewed by treated users.

Treated toxic users were also more likely to view a fewer number of posts during the intervention period, and this endogenous response changes the number of toxic posts viewed through the total number of posts viewed. This raises serious concerns that the main effects are driven by selection in the type of treated users who stay back on the platform, because users who disengage from the platform, or stop using it entirely, may be different from those who stay back.

I find that treated users were not more likely to leave the platform (to never login again after leaving) in the first three months of the intervention. Table H.4 shows that the treated leavers were not different from the stayers along any characteristics observable in the data.²⁵ This shows that selection cannot be driving the main results with respect to socially undesirable behavior.

5 Model

Personalization algorithms have been criticized for their role in radicalizing users by creating echo chambers of like-minded individuals, who may engage with toxic content (O’neil, 2017; Zuboff, 2019). I intervened upon online social networks by replacing the personalization algorithm with a ‘random algorithm,’ where users were recommended a random draw of posts on their social media feeds. This paper is organized around the costs and benefits of this intervention administered to randomly selected users. The costs of the intervention were borne by the platform as it led to a decrease in the time users spend on the platform, and hence, a decrease in the revenues generated from advertising. This is because treated users were not served personalized content, and were more likely to see content that they were not interested in.

On the other hand, the intervention offers benefits to society by reducing the number of toxic posts viewed. The intervention may indirectly compound these benefits due to behavioral responses of exposure. For example, users who were more likely to engage with toxic posts at baseline were shown more neutral posts, and this may influence them to positively change their minds about minority groups, and change sharing behavior accordingly. The model disentangles the costs and benefits of this intervention, when a policymaker’s objective is to reduce engagement with toxic content on social media.

5.1 Setup

User incentives are modeled in the spirit of Akerlof and Kranton (2000), where the user receives payoffs from projecting a certain image of herself to her peers. The user cares about how her action of sharing a post compares with reference to a combination of behavior among the population as well as one’s own true characteristics. This provides the micro-foundations

²⁵That is, I cannot rule out the hypothesis that, in the following regression equation, $\phi_{3,c}$ ’s are individually or jointly insignificant, $\mathbf{1}_i(\text{left platform}) = \phi_0 + \phi_1 D_i + \sum_c \phi_{2,c} \mathbf{1}_i(\text{user characteristic} = c) + \sum_c \phi_{3,c} \mathbf{1}_i(\text{user characteristic} = c) \cdot D_i + \varepsilon_i$, where, D_i is the treatment indicator, and $\mathbf{1}_i(\text{user characteristic} = c)$ represents indicator variables for observable characteristics c of user i , including gender, age, days since account creation, as well as weekday and daytime usage at baseline. This is complemented by evidence in Table H.3, which shows balance across treatment and control groups, along observable characteristics, in the sample of stayers.

to structurally estimate a behavioral model, where the main parameter of interest is the rate at which users update their engagement behavior when exposed to new content, that may be slanted (Martin and Yurukoglu, 2017).

The behavioral responses depend on user's exposure to content through the recommendation algorithm, which enables the user to perceive what is socially acceptable. This can aid policy instruments aimed at reducing engagement with harmful content, if diversified feeds expose users to alternative view points. However, other endogenous responses, driven by fixed tastes for different types of content, are likely to reduce the time a user spend on the platform, proving costly to the platform in terms of advertising revenues. The model shows the channels through which the costs to the platform and the benefits to society are realized.

5.1.1 Platform and Algorithm

The algorithm's objective is to optimize post assignment across various types of content to maximize user engagement with the platform.²⁶ I denote the probability of the algorithm assigning toxic and non-toxic posts as q^t and q^n , respectively. The total number of posts viewed by each user, denoted by N , is endogenously determined by the user for given probability assignments chosen by the algorithm. Therefore, the algorithm optimally chooses q 's to maximize N for each user, because a user who views a higher number of total posts also consumes a greater number of advertisements.

In optimizing the total number of posts viewed, the algorithm is essentially maximizing the attention paid to various advertisements hosted on the platform. This helps the platform increase the advertisement revenues it generates. Therefore, the firm is interested in maximizing the time users spend on the platform, which is sometimes measured using the total number of posts viewed. I abstract away from the exact process that translates views to advertising revenues.

The platform's problem is a simplification of the actual problem faced by social media platforms, where the platform also optimizes the number of likes and shares, as well as the number of ads shown to each user, and the price of advertising.²⁷ This greatly simplifies the analysis, because the rank of a post on the content feed is now reduced to a single number, the assignment probability. The objective is to mimic the incentives of a simple algorithm in order to analyze user responses, and not to analyze the algorithm itself.

²⁶The algorithm's objective function is known to *a priori* maximize the weighted sum of the number of posts a user will view, like, share, or comment upon. Section 2.3 provides a detailed discussion of how this objective function compares to other open source algorithms, for instance, the one used by X (formerly, Twitter). <https://github.com/twitter/the-algorithm>

²⁷While the platform employs its personalization algorithm to cater to user incentives, the modeled algorithm is a fairly coarse representation of more sophisticated technology. In this representation of reality, the recommendation process is simplified using assignment probabilities, in place of the embedding vectors described in Section 2.3. In a typical recommendation system, the dot product of user and post embeddings determines the *score* of each post that could be recommended to a user on her content feed. These scores determine the ranking of the posts on users' feeds, and the order of the posts is especially important for platforms optimizing for retention and engagement. I abstract away from these orderings, and assume that the assignment probabilities in the model are obtained by applying some sigmoid function (say, a logistic distribution) on the dot product of user and post embeddings. The assignment probabilities, are therefore, isomorphic to the embedding vectors in the actual algorithm.

5.1.2 User

Consider a social media user who chooses S^r posts of type- r to engage with (and in particular, to ‘share’), out of the total N^r posts of type- r posts viewed, where $r \in \{t\text{ (toxic)}, n\text{ (non-toxic)}\}$. Sharing is assumed to be costly for users, limiting the total number of posts she can share, $S = S^t + S^n$. Effectively, the user chooses the *proportion* of posts shared that are toxic as, $s^t = S^t/S$. She also picks the utility maximizing number of posts to view, $N = N^t + N^n$, for given assignment probabilities q^t and q^n .

Choosing s^r generates some *consumption utility*. The user obtains consumption utility from both viewing and sharing posts. However, users also have a taste for conformity, and derive *public recognition utility* from sharing posts that are closer to the average user’s action \bar{s}^t (Butera et al., 2022). The user’s objective is to maximize the utility she derives from sharing different types of posts. Then, consider a user’s decision to share toxic posts,

$$\begin{aligned} \max_{s^t, S, N} u(s^t, N; q^t, \beta, \alpha) = & \underbrace{\beta N - \alpha(N - S)^2}_{\text{consumption utility}} \\ & - \delta S \left(\underbrace{(1 - \theta) \left(\log \left(\frac{s^t}{p^t} \right) \right)^2}_{\text{disutility of deviating from own type}} \right. \\ & \left. + \underbrace{\theta \left(\log \left(\frac{s^t}{q^t} \right) \right)^2}_{\text{disutility of deviating from societal tastes}} \right) - \eta S^2 \end{aligned}$$

where, β is interpreted as users’ intrinsic motivation to *view* content or spend time on social media (Bénabou and Tirole, 2006). Additionally, α parameterizes users’ intrinsic motivation to *share* posts of type r , and p^t is the user’s preference parameter with respect to toxic content. The utility function implies that even when users receive positive utility from viewing another post (β), she incurs some disutility if the additional posts she views is not shareable, according to her tastes (α). $\eta > 0$ results in convex cost of increasing total number of posts shared, because sharing too many posts may reduce the attention paid to the user’s shared posts.

Crucially, a user’s behavior is reference dependent on the perception of society’s engagement behavior, q^t , as well as user’s own taste toward toxic content, p^t . Let $\delta S \left[(1 - \theta) \left(\log \left(\frac{s^t}{p^t} \right) \right)^2 + \theta \left(\log \left(\frac{s^t}{q^t} \right) \right)^2 \right]$ be the disutility when s^t is distinct from average behavior in the population, q^t , and one’s own true type p^t (Becker, 1991; Besley and Coate, 1992). In this *action-signalling* model, the user wants to conform with this average behavior, by choosing s^t that implies individual tastes close to everyone else’s tastes for toxic content (DellaVigna et al., 2012; Dupas et al., 2024). Therefore, $\theta \in [0, 1]$ is the weight users put on society’s perceived tastes for type- t content, because q^t reveals society’s preferences for toxic posts.

Notice that users' infer society's preferences using the probability with which toxic content is assigned to them by the algorithm, q^t , because engagement with a post is rapidly changing (Salganik et al., 2006). The algorithm assigns type- r content with probability q^r , and users infers that other users with similar characteristics also view such content with the same probability because of the personalization algorithm (Coate and Loury, 1993). I later show that this belief is indeed correct, because $q^t = p^t$ in the equilibrium.

The argument that users are sophisticated enough to infer society's tastes from the content they view on social media platforms is supported by survey evidence. In Figure G.5, I show that most users in the experimental sample believed that their engagement activity affects the feeds of other similar users on the platform. Further, these responses were not primed by the treatment itself. This is because treated users did not differentially observe that their feeds were not being personalized (Figure ??).²⁸ However, that treated users viewed fewer posts showed that the treatment was salient to the treated users. This is corroborated by the fact that treated users were more likely to disengage from the platform during the experiment.

The setup is consistent with the interpretation of algorithmically generated feed moving a user's Overton window, which is the range of ideas tolerated in public discourse (Astor, 2019). Users are assumed to understand that the algorithm provides similar recommendations to like-minded users. This enables users to update the perception of society's tastes for different types of content, and subsequently act in accordance with these norms to fit in with a potentially changing group identity (Kim and Loury, 2019).

Users are assumed to update their behavior in line with the perceived norms at some rate θ . It is worth noting that θ will ultimately serve as the measure of 'influence' on account of exposure to the algorithmically generated content feed. This is the main behavioral parameter of interest, that is estimated in the structural model.

Further, users in this model also derive utility from what their action reveals about their *true characteristics*, besides the identity of their social group. They incur a cost if their action signals characteristics that are different from their actual tastes (Mullainathan and Shleifer, 2005). Therefore, the disutility from sharing toxic content depends on how users' sharing behavior differs from a reference level which is given by a combination of what others do and their own unobserved intrinsic tastes.

Users solve an analogous optimization problem with respect to non-toxic content, as I assume that the parameter values are equal, with respect to both types of content.²⁹ The algorithm, in turn, learns the distortions in user behavior with respect to q^t , and makes content recommendations accordingly. This game unfolds according to the timing described in Appendix A, where I also solve for the subgame perfect equilibrium.

²⁸The survey questionnaire was ordered such that the question about noticing changes in the SM feed was asked after the question about the influence of engagement activity. This was done to ensure that the responses to the two questions were not correlated. The survey instrument is available in the Appendix.

²⁹The two optimization problems are identical because $q^n = 1 - q^t$ and $S^t + S^n = S$. The assumption of same parameters in both the utility functions is strong, but is validated later, in the discussion of the model.

5.2 Model Predictions

Consider two time periods in this model, so that $\tau = 0$ represents the baseline and $\tau = 1$ denotes the intervention period respectively. The algorithm assigns toxic posts to each user i at time τ with probability $q_{i,\tau}^t$, with $q_{i,\tau}^n = 1 - q_{i,\tau}^t$. The intervention is symbolically represented as the average of assignment probabilities in the control group ($\bar{q}_1^t = E[q_{i,1}^t | D_i = 0]$).³⁰ Therefore, I represent the treatment effect as the change in an outcome, with respect to changes in the exogenous probabilities assigned under treatment, all else equal. That is, the treatment effect is the partial derivative of an outcome with respect to \bar{q}^t .

With the given utility form, and the algorithm's optimization problem, and the timing of the game, the equilibrium conditions from the structural model (in Appendix A) provide a set of testable predictions. These predictions structure the analysis of the main results, and also shows that the model represents the data well. Then, the estimated parameters simulate reliable counterfactuals, for different policy regimes. First, the model predicts that the treatment effect on the total number of posts viewed is larger for more extreme users.

Proposition 1. *For user i with $\alpha, \eta > 0$, $\theta \in [0, 1]$ and $p_i^t > \bar{q}^t > 0$,*

$$\frac{\partial^2 N_{i,\tau}}{\partial p_i^t \partial \bar{q}^t} \geq 0 \quad (1)$$

That is, for marginal changes in the average probability of being assigned toxic content \bar{q}^t , users with higher proclivity to toxic content view more posts.

Proof. In Appendix B. □

When users prefer to engage with toxic content, marginal increases in assignment probabilities lead to larger increases in the total number of posts viewed, for more toxic users. This is because the treatment exogenously lowers the probability of being assigned toxic content to the control mean, so deviations from \bar{q}^t bring this probability closer to the user's true taste for toxic content, p^t . Therefore, the treatment effect on the total number of posts viewed is negative and smaller, and so has a bigger impact (in absolute terms) on more toxic users (Figure 3).

In Figure 2, I simulate the model predictions on the posts viewed, under two regimes: the treatment and the control.³¹ The control users continue viewing the optimal number of posts in equilibrium, but treated users are shown to view fewer posts. Indeed, the number of posts viewed is falling in user tastes for toxic content.³²

The model produces similar predictions for the total number of toxic posts shares, $S_{i,\tau}$. However, the utility maximization problem renders two solutions for the total number of posts shared, one of which is zero. I consider the non-trivial solution for the analysis.

³⁰ $\bar{q}_1^t = E[q_{i,1}^t | D_i = 0]$ because these probabilities are picked uniformly at random, each day during the intervention period, from the set of all possible assignment probabilities in the control group. Then, the Law of Large Numbers ensures probability convergence to the average assignment probability in the control group.

³¹See Appendix I for simulation details.

³²This is true for an arbitrary choice of parameters. The validated model produces the same results, when the parameters are calibrated by matching moments of the simulated data.

Proposition 2. For user i with $\alpha, \eta, S_{i,\tau} > 0$, $\theta \in [0, 1]$, and $p_i^t > \bar{q}^t > 0$,

$$\frac{\partial^2 S_{i,\tau}}{\partial p_i^t \partial \bar{q}^t} \geq 0 \quad (2)$$

That is, for marginal changes in the average probability of being assigned toxic content \bar{q}^t , users with higher proclivity to toxic content share more posts.

Proof. In Appendix B. □

The reduction in the total number of posts shared, on account of the treatment, is larger for users with higher proclivity to toxic content. The intervention is successful in reducing the number of toxic posts shared by toxic users, either by reducing platform engagement, or by influencing user behavior through. This result shows that both these mechanisms necessarily reduce toxic engagement from toxic users. However, for the non-toxic users, the disengagement mechanism can reduce toxic shares, but the behavior change or influence mechanism is likely to toxic shares.

The model makes pertinent predictions on the proportion of toxic posts shared, or the probability of sharing a toxic post, conditional on sharing, $S_{i,\tau}^t / S_{i,\tau}$. This is the main outcome variable, as it is informative about societal benefits of the intervention, in terms of discouraging toxic behavior (total number of toxic posts shared, $S_{i,\tau}^t$), relative to the costs borne by the platform, in terms of losing engagement (total number of posts viewed, $N_{i,\tau}$, and shared $S_{i,\tau}$).

Proposition 3. For user i with $\eta, N_{i,\tau}, S_{i,\tau} > 0$,

$$\frac{\partial^2 s_{i,\tau}^t}{\partial p_i^t \partial \bar{q}^t} \geq 0 \quad (3)$$

That is, a marginal increase from the average probability of assigning toxic content to the treated, \bar{q}^t , leads to larger increases in the proportion of shares that are toxic, for users with higher proclivity to toxic content.

Proof. In Appendix B. □

For the given rate of influence θ , the *decrease* in the proportion of toxic posts shared, on account of the treatment is larger for more toxic users. In particular, Figure 2 shows that the treatment effect on the proportion of toxic posts shared is negative for users with higher proclivity to toxic content, while it is positive for users with lower taste for toxic content. The model explains that the positive treatment effect on the proportion of toxic posts shared is likely driven by users with lower taste for toxic content. This is because there is a higher mass of users with lower taste for toxic content, where the treatment effect on proportion of shares that are toxic is positive.

These results demonstrate how different type of users respond differently to the treatment. If users were mechanical, they would all have constant effects such that the proportion of toxic posts shared is equal to the proportion of toxic posts viewed, irrespective of treatment status and time period. The comparative statics also show that the treatment effects on

toxic sharing are unlikely to be mechanical, because they seem to be larger for more toxic users. This means that users put a positive weight on the new information they receive, when making sharing decisions. The users are considered to be ‘behavioral’ in this sense.

The changes in toxic sharing would be mechanical if the proportion of toxic posts shared is equal to the proportion of toxic posts viewed, in each time period.³³ This is because the users share a fixed fraction of the toxic posts they view, and the algorithm served the toxic posts according to the same proportion, p_i^t . In other words, ‘mechanical’ users would continue sharing posts in the same proportion, without updating their behavior according to the new information they receive, when they are treated, i.e. $\frac{S_{i,\tau}^t}{S_{i,\tau}} = \frac{N_{i,\tau}^t}{N_{i,\tau}}$.

The model predicts mechanical behavior if and only if the influence parameter, θ equals 0 for mechanical users. Before estimating θ in the structural model, I show that this parameter is in fact non-trivial.

Proposition 4. *User i with $N_{i,\tau}, S_{i,\tau} > 0$, is said to behave ‘mechanically’ when*

$$\theta = \beta = \eta = 0$$

That is, when $\theta = 0$, the elasticity of the proportion of toxic posts shared with respect to the proportion of toxic posts viewed is 1.

Proof. In Appendix B. □

Users are thought to behave mechanically if the elasticity of toxic sharing with respect to toxic viewing equals 1. The data suggest that this elasticity is less than 1, implying that there are decreasing returns to sharing more toxic posts, upon being exposed to an additional one. The empirical results are interpreted in light of these predictions, and the main parameter of interest θ is estimated using this structural model.

5.3 Structural Estimation

The framework builds a model of user behavior to explain the channels through which the random algorithm reduces engagement with toxic content. User behavior could either be sticky according to baseline preferences, or could be malleable on account of new information users are exposed to. The model provides an estimation strategy for the rate at which users update their sharing behavior, θ , in line with what they think is socially acceptable.

5.3.1 Measurement

The data $\mathcal{D}_{i,\tau} = \{S_{i,\tau}^t, S_{i,\tau}^n, V_{i,\tau}^t, V_{i,\tau}^n\}$ consists of measurements on number of toxic and non-toxic posts viewed and shared by each user, during the intervention period ($\tau = 1$) and the baseline period ($\tau = 0$). I measure sharing probabilities during the intervention period as, $s_{i,1}^r = \frac{S_{i,1}^r}{S_{i,1}}$, for $r \in \{t, n\}$. That is, the probability of sharing a toxic posts is the proportion of toxic shares out of all the posts shared by user i .³⁴

³³This is formally proved in a companion paper studying the effect of exposing users to local news on their engagement with toxic content.

³⁴Strictly speaking, this is the probability of sharing a toxic post, conditional on sharing any post. If a user does not share any post, this probability is set to zero in the data.

I imperfectly measure users' innate preferences with their sharing behavior at baseline ($\tau = 0$), i.e. $p_i^t \equiv s_{i,0}^t$ and $p_i^n \equiv s_{i,0}^n$. This is true because user behavior at baseline is said to be in equilibrium, and it has been seen that $q_{i,\tau}^t = p_i^t$. Therefore, Lemma A.1 implies that $s_{i,0}^t = p_i^t$ in equilibrium.

Similarly, I proxy user's probability of being assigned toxic content with the proportion of toxic posts viewed, i.e. $q_{i,\tau}^t \equiv v_{i,\tau}^t$. The model predicts that in equilibrium, the optimizing algorithm assigns toxic content in line with users' tastes for viewing different types of content. This is important because the probability of being assigned toxic content is not observed during the first month of the intervention.

That is, in arriving at the estimation strategy, I assume that a user views all the posts she is assigned by the algorithm. This means that $N_{i,\tau}^t = N_{i,\tau} q_{i,\tau}^t \equiv V_{i,\tau} q_{i,\tau}^t = V_{i,\tau}^t$, where $V_{i,\tau}$ and $V_{i,\tau}^t$ formally denote the total number of posts viewed, and the number of toxic posts viewed respectively. I later relax this assumption, and employ a measurement error correction to account for the fact that users only view a proportion of the posts they are assigned.³⁵ Then, the equilibrium sharing probabilities in Lemma A.1 are represented as functions of sharing behavior at baseline, and views during the intervention period.

Proposition 5. *The optimal sharing functions are written as*

$$\log s_{i,1}^t = (1 - \theta) \log s_{i,0}^t + \theta \log v_{i,1}^t + \mu \log w_i^t \quad (4)$$

$$\log s_{i,1}^n = (1 - \theta) \log s_{i,0}^n + \theta \log v_{i,1}^n + \mu \log w_i^n \quad (5)$$

where, w_i^t and w_i^n are taste-based, and time invariant preference shocks for sharing a post. I postulate that users change their behavior in response to the treatment as they infer society's tastes for different types of content they view. Accordingly, users update their sharing behavior, at some rate θ , to remain in step with other similar users. Then, the main structural parameter, θ , represents the influence of exposure to toxic content on user behavior, or the rate at which users expand their Overton windows. This interpretation of the main parameter of interest, θ , is in line with the idea that users expand their view of socially acceptable things to say in public discourse, by observing the content that is recommended to them by the algorithm.

Proposition 5 gives the required sharing functions that I base the structural estimates off. I estimate the model in order to identify the role of users' innate preferences, separately from the rate at which users update their behavior in response to changes in the algorithmic recommendations. θ cannot be directly estimated through equations (4) due to certain features of the experiment's design, which are in Appendix C.1.³⁶ A steady state condition is used to identify θ .

³⁵The measurement error is an important factor in the estimation strategy, as treated users randomly sample posts to view from some list of posts assigned by the algorithm. Therefore, the proportion of toxic posts viewed follows a known sampling distribution, which is discussed in detail in Appendix C.3.

³⁶The main issue is that there is insufficient variation in proportion of toxic posts viewed for both treated and control users. This is true for control users probability of sharing toxic content is equal in the steady state equilibrium. This is true for control users because they are exposed to a constant proportion of toxic content, \bar{q}_1^t .

5.3.2 Steady State

This system of interaction between recommendation algorithms and social media users is said to be in steady state when the probabilities of assigning toxic and non-toxic posts ($[q_{i,\tau}^t, q_{i,\tau}^n]$), as well as the probabilities of sharing toxic and non-toxic posts ($[s_{i,\tau}^t, s_{i,\tau}^n]$) are stable over time. The steady state condition is also the *identifying condition* as it states that in the absence of any exogenous changes to assignment probabilities, user behavior should be the same in each time period. As a result, any changes in the probabilities of sharing toxic content are due to changes in exposure to toxic content. This allows for the identification of the updating parameter θ , which does not change over time or by treatment status.

At $\tau = 1$, users in the control group remain in the steady state, which means that θ cannot be correctly estimated using data on shares and views for control users. This is because the proportion of different types of content viewed by control users, is correlated with sharing behavior at baseline, on account of the assignment probabilities generated by the algorithm.

Lemma 1. *θ cannot be identified from the relationship between sharing behavior and the proportion of toxic content viewed during the intervention period among a sample of control users.*

Proof. In Appendix B. □

The resulting steady state conditions provide the main identifying assumptions because endogenous sharing behavior at $\tau = 1$ or $\tau = 0$ is *a priori* expected to be equal for treated users. That is, in the sample of treated users, θ is identified when the following assumptions are satisfied,

$$s_{i,0}^t = (v_{i,1}^t(\bar{q}^t))^{\theta} (w_i^t)^{\mu} (s_{i,0}^t)^{1-\theta} \quad (\text{A2})$$

$$s_{i,0}^n = (v_{i,1}^n(\bar{q}^n))^{\theta} (w_i^n)^{\mu} (s_{i,0}^n)^{1-\theta} \quad (\text{A3})$$

I test and discuss this assumption in greater detail in Section ???. Given these identifying assumptions, θ can be estimated using data on current and past shares because $\bar{q}^t \perp s_{i,0}^t$ and $\bar{q}^n \perp s_{i,0}^n$.

Proposition 6. *For some updating parameter θ , and treated user i , the change in ratio of toxic-shares to non-toxic shares from the baseline is a function of the log-odds ratio of the proportion toxic posts viewed at baseline. That is,*

$$\log \left(\frac{s_{i,1}^t}{s_{i,1}^n} \right) - \log \left(\frac{s_{i,0}^t}{s_{i,0}^n} \right) = (1 + \theta) \log \left(\frac{\bar{q}^t}{\bar{q}^n} \right) - \theta \log \left(\frac{v_{i,0}^t}{v_{i,0}^n} \right) \quad (6)$$

Proof. In Appendix B. □

Intuitively, the constructed outcome in Proposition 6 accounts for unobserved differences in preference for sharing any type of content.³⁷ Details of the estimation are provided in Appendix C.

³⁷The difference in exposure to different kinds of content, between baseline and intervention period provides heterogeneity in treatment intensity, which is exogenous to user tastes. The first differences over time, within

5.4 Discussion

I use a structural model to formalize the analysis for the following reasons. First, the model's equilibrium characterization of user types allows the decomposition of user behavior into its mechanical and behavioral components (in Appendix A), in a meaningful way. In assigning random draws of posts to treated users, the intervention directly reduced the proportion of toxic posts viewed by users who engaged with more toxic content at baseline. This mechanically left such users with fewer options to share toxic content from.

Second, the model provides micro-foundations for user engagement with harmful content. The treatment altered the perception of society's tastes for toxic content, which users infer from the realized sequence of posts that appear in their feed. Users update their view of socially acceptable content in order to conform with other users of similar type (Akerlof and Kranton, 2000; Fang and Loury, 2005). Treated users were served an average user's feed, and thought to update their opinion of what other users of the same type might be viewing. This is supported by the survey evidence, as both treated and control users were likely to believe that their engagement activity affects the feeds of other similar users on the platform (Figure G.5).

Third, the model decomposes the treatment effect into two channels, (1) the endogenous response in the total number of posts viewed and shared, and (2) the influence of exposure to diverse content on the proportion of toxic posts shared. Treated users endogenously responded to diversity in content assignment by viewing fewer posts, or spending less time on the platform. However, the model shows that this effect was more pronounced for users who were previously engaged with more extreme toxic content (henceforth, toxic users).

The action-signalling model (Butera et al., 2022) helps in disentangling users' endogenous response on the total number of posts viewed from the mechanical and behavioral effect on the proportion of toxic posts shared. This is important because the former provides accurate estimates of the cost of the intervention to the platform, while the latter predicts the role of behavioral distortions in driving the treatment effect on toxic sharing. For users more likely to engage with toxic content at baseline, all these channels drive the exposure to and engagement with toxic content downward. This provides valuable information to a regulator interested in policies that reduce the total amount of toxic content shared on social media platforms.

The structural model estimates the malleability of user behavior by identifying θ . However, in so doing, it makes a set of assumptions that are validated below.

5.4.1 Simplifying Assumptions

In writing the utility for structural estimation, I made four simplifying assumptions: (1) consumption as well as signalling utilities are additively separable for each content type, (2) action-signalling utility from *sharing* is equal for both types of content, i.e. $\theta^t = \theta^n = \theta$, (3) user behavior in the action-signalling model is updated at some constant rate θ across all

the treatment group, accounts for unobserved heterogeneity in sharing behavior. Since, exposure to toxic content among the treated during the intervention period is constant on average, the estimates from this differencing strategy effectively only uses variation in baseline exposure among toxic users. As a result, θ can be identified using the relationship between *difference in shares* (from $\tau = 0$ to $\tau = 1$) and *levels of views at baseline* ($\tau = 0$) in the sample of treated users.

users, (4) deviating from the reference point of own and society's tastes generates disutility which is quadratic in nature.

The first assumption rules out strategic complementarities and substitutabilities between different kinds of posts (Train, 2009). This is tenable due to the fact that users scrolling through social media are assumed to be viewing posts one at a time, and do not know if the next post they will view is going to be toxic or not. Additionally, the path dependency of user behavior on the distribution of all types of posts is modeled separately through the utility from action-signalling.

I test the second simplifying assumption, as I can observe whether the signalling value from sharing toxic and non-toxic content is equal. This assumption is validated in Table H.6, as I test for the equality of coefficients using stacked regressions. The two regressions estimate the relationship between toxic views and toxic shares, as well as non-toxic views and non-toxic shares. I cannot reject the hypothesis that the coefficients from these regressions are equal.

I test the third assumption, that is, the constant effects with respect to the rate of updating user behavior in the action-signalling model. Figure G.10 supports this assumption, as the estimates of θ obtained from samples of different 'types' of users are indistinguishable from each other. Therefore, I cannot reject the hypothesis that the rate of updating user behavior is equal across different types of users.

Finally, I have assumed the costs of using social media to be quadratic for ease of computation. The model does not stray far from the literature on strategic interactions in the presence of social signalling, especially when such models are estimated using structural methods, for instance, in Butera et al. (2022).

5.4.2 Identifying Assumptions

The main identifying assumption in this framework is that the probability of sharing toxic content is equal in steady state equilibrium. Since, the control users remain in steady state during the intervention and were chosen randomly, I test this assumption in the sample of control users,

$$s_{i,0}^t = s_{i,1}^t \quad (\text{IA})$$

In order to test this assumption, I estimate parameters of the following regression,

$$s_{i,1}^t(D_i = 0) = \delta_1 s_{i,0}^t(D_i = 0) + \varepsilon_{i,1}$$

Under this identifying assumption (IA) I expect $\delta_1 = 1$ in the sample of control users. As before, I correct for measurement error in computing the proportion of toxic posts shared. Table H.7 shows that I cannot reject the hypothesis that $\delta_1 = 1$, in the measurement error corrected case.

6 Results

The given framework structures the analysis of my intervention, which turns off the algorithm for a random subset of users. With different magnitude of effects for different types of users, the model decomposes the effect of changing exposure to toxic content, into two channels:

change in user behavior due to the change in exposure, and change in overall engagement with the platform.

6.1 Testing Model Predictions

The model allows a characterization of user types in terms of baseline exposure to toxic content. I analyze the main outcomes separately for users in different quantiles of baseline exposure to toxic content, or the distribution of proclivities to toxic content. The first quantile, Q1, represents users with lower taste for toxic content. On the other hand, users in Q5 have a higher taste for toxic content, and are expected to be most affected by the treatment, due to the reduction in exposure to toxic content.

Prediction 1: Number of toxic posts viewed Upon being treated, toxic users (or users with higher baseline exposure to toxic content) view far fewer toxic posts during the intervention period. Lemma A.5 shows that the equilibrium assignment probabilities exactly equal respective users' tastes for such content, i.e. $q_{i,\tau}^t = p_i^t$ for all i in the control group. If user i were to be treated, she instead receives toxic content in her feed with probability \bar{q}^t in time period $\tau = 1$. Then, the model prediction on treatment intensity, or the proportion of posts viewed that are toxic, during the intervention period, is stated as

$$v_{i,1}^t(D_i = 1) - v_{i,1}^t(D_i = 0) = \begin{cases} \bar{q}^t - q_{i,\tau}^t & \text{if } p_i^t > \bar{q}^t \\ 0 & \text{if } p_i^t = \bar{q}^t \\ \bar{q}^t - q_{i,\tau}^t & \text{if } p_i^t < \bar{q}^t \end{cases}$$

That is, $\bar{q}^t - q_{i,\tau}^t < 0$, for more toxic users with $p_i^t > \bar{q}^t$ as \bar{q}^t is the average user's probability of being assigned toxic content. Similarly, the treatment intensity is positive for users who dislike toxic posts, because $\bar{q}^t - q_{i,\tau}^t > 0$ if $p_i^t < \bar{q}^t$. The treatment intensity is smallest (in absolute terms) for the neutral users with $p_i^t = \bar{q}^t$.

The *simulated* experiment and recommendation algorithms also show that the treatment effect on the assignment probabilities is negative, and smallest in absolute terms for the most neutral users. In Figure 1, the absolute value of simulated treatment intensities are highest for extreme users, mechanically. In the experiment, the decrease in exposure to and engagement with content for more toxic users is, in part, due to the reduction in the total number of posts viewed. Therefore, exposure is also affected by users endogenously reducing their time spent on the platform, and this response may also differ by user type.

Figure 3 shows that the treatment effect on the number of toxic posts viewed is negative for toxic users. Additionally, Figure 5 shows that the treatment effect on the proportion of toxic posts viewed is negative for toxic users. This Figure also shows that the treatment effect on proportion of views that are toxic is positive and statistically significant for non-toxic users. However, the absolute value of the negative effects are larger than the positive effects observed for non-toxic users. These results are key in predicting the treatment effects on the remaining outcomes, separately for different types of users.

Prediction 2: Total number of posts viewed Figure G.1 shows that, on average, the treatment was likely to reduce the total number of posts viewed by users. The model,

however, makes a finer prediction: the treatment effect on the total number of posts viewed is likely to be negative and larger (in absolute terms) for toxic users.

Figure 2 shows predictions from the simulated model, under the equilibrium conditions. Here, I compare key quantities that are produced by the equilibrium conditions generated by the model under two regimes, **(1) treatment**: where assignment probabilities are allocated randomly, and **(2) control**: where assignment probabilities are allocated according to an optimizing personalization algorithm. I find that the distance between number of posts viewed, under the two regimes, is largest for users with more extreme tastes for toxic content, p^t . This confirms the prediction in Proposition 1 that treated users, with a higher proclivity to toxic content, viewed fewer posts during the intervention period.

Indeed, Figure 3 shows that the treatment effect on the total number of posts viewed is negative, and larger in absolute terms, for toxic users. Note that the model predicts no change in the total number of posts viewed for users who were viewing average quantities of toxic content at baseline. That is, if 2% of the post corpus contains toxic content, then users with 2% toxicity in their baseline feeds are likely to view the same proportion of posts during the intervention period.³⁸ As a result, the treatment may not be salient for these users, as there is no change in the total number of posts viewed.

In fact, Figure 2 shows that the prediction can be applied to both extreme ends of the toxicity distribution, as the treatment effect on the total number of posts viewed is also negative for users who viewed less toxic content at baseline. That is, users on the other extreme of the toxicity distribution (i.e. non-toxic users in Q1) are also expected to view fewer posts, or spend less time on the platform in total. This is because, in the model, exposure is assumed to have constant effects on user behavior, irrespective of user type. Therefore, user responses are assumed to be symmetric along the toxicity distribution.

Figure 3 shows that the treatment effect on the total number of posts viewed is insignificant for users in Q1. This points toward the possibility that user responses are not symmetric across the distribution of user types. Although Figure ?? shows that the hypothesis that θ values are different for different user types cannot be rejected, I cannot conclude that these are homogenous either. In fact, Figure G.12 shows that relaxing the symmetry assumption provides model predictions that are consistent with the empirical results. I tackle this in greater detail later, when calibrating model parameters to simulate counterfactual policy outcomes.

Prediction 3: Total number of posts shared Figure G.1 shows that the intervention led to a decrease in the total number of posts shared, for the average user. However, Proposition 2 predicts that the treatment effect on the total number of posts shared is negative but larger in absolute terms, for users with higher proclivity to toxic content, because $\frac{\partial^2 S}{\partial q^t \partial p_i^t} > 0$. Figure 4 shows that this is indeed the case, as the absolute value of the treatment effect for users in Q1 is the smallest.

Notice that the magnitude of the treatment effect remains stable for users, even in the upper quantiles of Figure 4. In Figure 2, the model predicts that when proclivity to toxic content is high enough, the treatment effect on the total number of posts shared decreases

³⁸2% toxicity in baseline feeds means that 2% of the posts viewed by the user, on their main feed, are toxic.

at a much slower rate. This is consistent with the interpretation that sharing behavior is not malleable for users with high enough proclivity to toxic content. As before, relaxing the assumption of constant θ for all user types generates predictions that are consistent with the empirical results (Figure G.12).

Prediction 4: Proportion of posts shared that are toxic Proposition 3 shows that the cross-partial derivative of the proportion of toxic posts shared with respect to the assignment probabilities and user proclivity to toxic content is positive. Intuitively, this means that marginal increase in the proportion of toxic posts viewed due to the treatment, only changes sharing behavior by an order of θ , through the channel of influence from exposure. Then, users with higher p_i^t are likely to have a larger response (in absolute terms) to treatment.

Figure 2 predicts that the absolute value of the treatment effect on the proportion of shares that are toxic (S^t/S) is the largest for users with higher proclivity to toxic content. The model also predicts that the treatment effect is positive for users who do not prefer toxic content, and negative for users who prefer toxic content. This is seen in Figure 2 and verified in Figure 5. The treatment effect on proportion of shares that are toxic is seen to be positive in Q1, and negative in Q5.

A regulator or social planner is likely interested in behavior change caused by the intervention, with respect to the total number of toxic posts shared. However, the ratio of toxic shares to total shares is informative about the composition of shares, and the extent to which users are engaging with toxic content. It is instructive to learn s^t as it helps analyze if the average reduction in toxic sharing is stemming from the influence of exposure on behavior, or if it is driven by disengagement with the platform.

Prediction 5: Mechanical Effects The model predicts that if exposure has no influence of user behavior, i.e. $\theta = 0$, users tend to behave mechanically. That is, when $\theta = 0$, users share a fixed proportion of toxic content they view, in each time period.³⁹ The negation of this implication is also true, and is tested empirically to analyze if user behavior is malleable or sticky. That is, if users do not behave mechanically, then exposure has an influence on user behavior, i.e. $\theta > 0$.

I find that the treatment effect on the proportion of toxic posts shared is distinct from the effect on the proportion of toxic posts viewed. Intuitively, the equality of these two ratios indicates mechanical behavior, because this is the case of unit elasticity of toxic sharing with respect to toxic viewing. I reject the hypothesis that the elasticity equals 1, because the χ^2 statistic from the non-linear test of equality between ratios is 9.44, with a p-value of 0.002.

These empirical results clearly show that there are behavioral responses to diversifying content feeds, even though the influence of exposure is relatively small, as I will show in the estimation of the structural model. The prediction helps negate the possibility that $\theta = 0$, which is the case of no updation in user behavior with respect to exposure. Then, behavior is said to be mechanical because users share the same proportion of toxic content they view, in each time period. This sets up the rationale for estimating the structural model.

³⁹The formal proof of this statement is found in a companion paper.

6.2 Complimentary Evidence

The inelasticity of toxic sharing with respect to toxic viewing implies that when a platform censors toxic content, users are unlikely to change their attitudes or behaviors. This is because users can seek out the content they want to engage with, irrespective of the algorithm's recommendations. One way users can seek out content is by directly searching for it. In Table H.2, I find that treated users were more likely to use the platform's text search feature.

The varying treatment intensities also imply that users with higher treatment intensities should search more. This is because they were assigned less relevant content, and this effect is expected to be larger for users who saw more toxic content at baseline. Indeed, in Figure 6, I find that Q5 users were more likely to search posts they wanted to engage with.

Note that this is consistent with my finding about negative effects on the number of posts viewed by toxic users because my measure of posts viewed only considers exposure through the 'Trending Feed,' which is the landing page of the platform. Therefore, the additional posts that users may have discovered and viewed through the search feature, are not included in the measure of views. Additionally, this effect is likely to be small because searched posts comprise 0.1% of posts viewed, and 0.04% of posts shared.⁴⁰

Figure 6 shows that the treatment effect on the ratio of toxic shares to toxic views is monotonically increasing in user toxicity. The implication is that toxic users share a larger proportion of toxic content they are served, by scrolling past the posts they do not want to engage with. That is to say, toxic users were more likely to share a toxic post when they found one, but non-toxic users were not more likely to share toxic content even when the algorithm exposed them. This is also consistent with the assertion that low-type users have lower θ , or are even less malleable than users with a higher taste for toxic content.

This is reflected in the fact that even though treated users spent significantly less time on the platform, there were no significant differences between the treatment effects across different types of users (Figure G.6). Note that the intervention only randomized the posts on the landing page, making this a more likely explanation for the observed treatment effects.

Finally, Figure G.7 shows that the margin of adjustment in platform engagement mostly comes from reduced usage during working hours. This is because treated users were less likely to use the app during the day, and were more likely to log in during the evenings and weekends (Table H.2). This has important implications for technology policy around questions of platform usage and digital addiction, that are currently beyond the scope of this paper.

6.3 Structural Estimates

A difference-in-difference estimator measuring the elasticity of toxic shares with respect to toxic views is not estimable among control users because the proportion of toxic views and toxic shares is in steady state. This necessitated the need for a structural model, as explained in Appendix C. I estimate the structural relationship between the differences in probability of sharing toxic content over time, and the proportion of toxic posts viewed at baseline, using

⁴⁰This was true later in the post-period, August 2024. I cannot verify this for the intervention period, but there is no reason to believe these numbers would be any different.

the following specification,

$$(s_{i,1}^t - s_{i,1}^n) - (s_{i,0}^t - s_{i,0}^n) = \gamma_0 + \gamma_1(v_{i,0}^t - v_{i,0}^n) + \varepsilon_{i,1} \quad (7)$$

where, $\varepsilon_{i,1}$ is assumed to be a random error term. This exercise is performed using a sample of treated users only, and it estimates the share of toxic engagement that is driven by user behavior at baseline via the feed-ranking algorithms. The resultant estimates are correctly identified because the treated users are exposed to toxic content during the intervention period purely by chance, therefore eliminating endogeneity in viewing and sharing over time.

It has been shown that if the relationship of interest is linear, then $\hat{\gamma}_1 = -\hat{\theta}$ (Appendix C.2). I first assess if the relationship between these two variables is linear in Figure G.11a. Due to the skewness of the distribution of toxic views at baseline, I flexibly fit the probability of sharing toxic content with respect to the difference in the proportion of toxic posts and non-toxic posts viewed at baseline (as an approximation to the relevant log-ratios, henceforth referred as simply the difference).

The function in Figure G.11a approximates a linear relationship between the difference in toxic and non-toxic exposure at baseline and the difference in these differences over time, or current engagement with toxic content, in the treatment group. This shows that a linear fit is appropriate for the data.

6.3.1 OLS Estimates

Table H.8 shows that the estimated effect of a 1% decrease in the proportion of toxic posts viewed during the intervention period decreases the change in proportion of toxic posts shared by $\hat{\theta}\% = 0.08\%$. This also demonstrates that the estimated stickiness in user behavior, or the elasticity in sharing behavior with respect to baseline sharing behavior, $(1 - \hat{\theta})$ is close to 0.92. Therefore, upon being exposed to toxic content randomly, users barely update their behavior in line with content they saw during the intervention period.

These estimates support the claim that user behavior is not malleable, and is largely determined by user preferences at baseline. However, these OLS estimates of θ are likely to be suffer from attenuation bias. This is because the data on proportion of toxic or non-toxic posts viewed is likely to suffer from measurement error, due to the fact that users sample a fraction of posts to view, after the algorithm assigns them to the feed. I use an IV estimation strategy outlined in Appendix C.3, to correct for this possibility.

6.3.2 IV Estimates

The IV estimates, in Column (2) of Table 1, indicate that the measurement error indeed led to attenuation bias in the main OLS estimates shown in column (1) of Table ???. The first column in Table 1 shows the strength of the first stage for the IV specification, where I instrument average toxicity in the first half of the posts viewed at baseline, with the average toxicity in the second half. The measurement error corrected estimate shows that a 1% reduction in exposure to toxic content reduces engagement with toxic content by 0.16%.

The IV strategy provides the preferred estimate of the elasticity of sharing toxic content with respect to viewing toxic content. More standard approaches for correcting classical linear measurement error provide larger estimates of θ . This first stage also serves as a

measure of reliability for the main outcome variable, in STATA’s in-built measurement error correction program, whose result is shown in column (3).

The lack of flexibility in user responses has serious implications for designing regulatory policies aiming to reduce engagement with toxic content in digital spaces. My results indicate that the elasticity of the odds of sharing toxic content, with respect to exposure at baseline is more than 0.84. This leaves little room for policy instruments to alter sharing behavior through reduced exposure to toxic content, by influencing behavior through exposure to more desirable content. Note that reductions in exposure to toxic content does not have a one-to-one relationship with change in sharing behavior. Table 1 shows that user behavior significantly depends on pre-existing behaviors or preferences.

These results are consistent with a model of user behavior where user response is determined by both current and previous exposure to toxic content, where previous exposure is endogenously determined by the algorithm, according to user preferences. This means that while users update their behavior in line with new information that they are exposed to, a significant part of their behavioral responses are sticky as they depend on user behavior at baseline. I perform a series of checks to validate these structural estimates in Appendix C.4.

6.4 Model Based Counterfactuals

I calibrate the model parameters to estimate the counterfactual effect of reducing exposure to toxic content. This is done by matching moments of the empirical distribution of the total number of posts viewed and shared, as well as the total number of toxic posts shared, with the simulated moments generated using the model with θ set at 0.16. The calibration exercise, for various model parameters, is summarized in Table H.10, and detailed in Appendix C.5.

6.4.1 Alternative Behavioral Assumptions

I simulate the counterfactual effects of the intervention, under different assumptions on user behavior. That is, I use the calibrated model parameters to construct counterfactual distributions of the treatment effects, when users share toxic content appearing on their feed mechanically (i.e. $\theta = 0$), and when users fully update their behavior in line with new information (i.e. $\theta = 1$). Figure G.14 shows that malleable users with $\theta = 1$, the percentage change in number of toxic posts shared is decreasing user type. This is because more toxic users viewed fewer toxic posts, and are more likely to be influenced when $\theta = 1$. This Figure also shows that malleable users with low proclivity to toxic content would view and share a higher number of toxic posts, upon being treated.

The case of mechanical users confirms that treatment leads to no change in the number of toxic posts shared, or in its constituent parts. Finally, under the assumption of constant behavior across user types, $\theta = 0.16$ implies that the treatment effect on the number of toxic posts shared approximates an inverted V, when plotted against user toxicity. Since I am interested in behavior change of toxic users, I focus on the right-hand side of the distribution of user types. Here, the decrease in number of toxic posts shared is larger in absolute terms when users are malleable ($\theta = 1$), than when the users behave according to the observed degree of malleability, $\theta = 0.16$.

6.4.2 Treatment Effect Decomposition

Next, for the calibrated model parameters, including $\theta = 0.16$, I decompose the treatment effect on the total number of toxic posts shared into two channels: **(1) Engagement:** the change in engagement with the platform, or the number of posts of any kind, that were viewed and shared by treated users, and **(2) Influence:** the change in the probability of sharing toxic content, given the number of posts shared. Simply put,

$$S_{i,1}^t = N_{i,1} \cdot \frac{S_{i,1}}{N_{i,1}} \cdot s_{i,1}^t$$

$$\implies \% \text{ change in } S_{i,1}^t = \underbrace{\% \text{ change in } N_{i,1}^t + \% \text{ change in } \frac{S_{i,1}}{N_{i,1}}}_{\text{change in engagement}} + \underbrace{\% \text{ change in } s_{i,1}^t}_{\text{change in influence}}$$

For θ estimated at 0.16, I simulate the effect of exogenously changing \bar{q}^t for different types of users, and analyze how these two components of the treatment effect change the number of toxic posts shared. Figure G.15a shows that the treatment effect on total number of posts viewed and shared reduces the treatment effect on the number of toxic posts shared, and is negative for more toxic users. For this low value of the influence parameter, the decreasing effect on the probability of sharing toxic Content seems to be largely driven change in engagement (both views and shares). This means that even when θ is low enough, the negative effect on the number of toxic posts shared is dominated by the engagement effect.

In this counterfactual decomposition, the influence effect, represented by s^t , is surely decreasing in user toxicity. However, the decrease in N is even larger, with increasing toxicity in user-type. Note that, when users are fully malleable with $\theta = 1$, as in Figure G.15c, the treatment effect in number of toxic posts shared in entirely driven by the influence effect, or the change in proportion shares that are toxic, s^t .

6.4.3 Counterfactual Policies

Finally, the model predicts the main outcomes, for different policies that can be implemented. It is hard to conceive of a policy where platforms would agree to turn off their algorithms for all their users, and deliver posts by a random draw instead. It is however, completely realistic to imagine a policy where platforms are required to diversify their feeds, by randomizing a portion of the posts that users see.

Randomizing part of the feed makes for good policy because the platform algorithm can learn about changing, and sometimes inconsistent, user preferences, from their engagement with randomly served content (Kleinberg et al., 2022). Platforms typically want to be at some point on the exploration-exploitation frontier, where they are able to retain users by showing them content they like, and continuously learning about their preferences (Zhan et al., 2021). This paper shows that introducing diversity into feeds may also be beneficial from a societal viewpoint, as it may persuade users to share less toxic content.

A social planner may be interested in the optimal mix of algorithmic and random feeds, also because personalization algorithms have been demonstrated to hold high value for the users themselves. Therefore, I simulate the main policy outcome, number of toxic posts

shared, and its component parts, under different mixes of algorithmic and random feeds in Figure 7. This shows that even when 60% of the feed is randomized, the effect on toxic sharing for toxic users is driven by the influence effect, or the change in the probability of sharing toxic content, given the number of posts shared (s^t). However, the social gains in terms of reduction in toxic sharing are fairly limited.

On the other hand, if at least 80% of the feed is randomized, the effect on toxic sharing for toxic users is driven by the engagement effect. Under the assumption of constant θ , the platform loses both extremely toxic and non-toxic users. If a platform is willing to admin that $\theta = 0$ for non-toxic users, then the complete randomization strategy would still benefit societal gains. This is because the decrease in toxic engagement is driven by toxic users disengaging with the platform. This may be consistent with a planner’s objective. At any rate, this counterfactual exercise shows that a planner can optimally choose a degree of randomization, to balance the trade-off between user engagement with social media platforms, and the dissemination of toxic content. Table H.11 shows the contribution of each component, under different policy regimes, for the average user.

7 Conclusion

Content recommendation algorithms are often accused of boosting engagement with misinformation, like hate speech, on social media platforms, all around the world (Pariser, 2011; Weinstein et al., 2021; Fisher, 2022).⁴¹ Personalization algorithms have also been linked to hate-crimes and politically motivated violence. The failure to prevent incitement to violence has brought these platforms under scrutiny, especially in the case of the Capitol Hill riots on January 6, 2021 in Washington DC,⁴² as well as the recent indiscriminate killings in Myanmar and Ethiopia.⁴³ In a congressional hearing on social media’s role in extremism in March 2021, Rep. Mike Doyle (Pa.) addressed chief executives of Google, Facebook, and Twitter, “the power of this technology is both awesome and terrifying, and each one of you has failed to protect your users and the world from the worst consequences of your creations.”⁴⁴

It is, however, unclear if these harms are propagated solely due to algorithmic exposure to toxic content, or by users’ pre-existing preferences over such content. This is because the algorithms are optimized to enhance user satisfaction using revealed preferences that the algorithm learns from users’ engagement in the past. On the other hand, user preferences for content could be influenced by the content they view, so that users can convincingly signal that they are engaging with posts that are perceived to be popular in their network.

This paper studies the role of user preferences and personalization algorithms in driving engagement with extreme content. I conducted a large-scale randomized evaluation of such algorithms by effectively turning it off for one million treated users, on a popular TikTok-like platform in India. This ensures that the content users are exposed to during the intervention

⁴¹See also, <https://www.techtransparencyproject.org/articles/two-studies-social-media-algorithms-fuel-online-hate>

⁴²See <https://www.nytimes.com/2021/03/25/business/jack-dorsey-twitter-capitol-riot.html>

⁴³See <https://bit.ly/3smUoUE>

⁴⁴See <https://www.washingtonpost.com/technology/2021/03/25/facebook-google-twitter-hearing/>

is uncorrelated with their behavior and therefore, distinguishes the influence of technology from that of human behavior. I examine whether the content presented by algorithms substantially impacts user choices, or if, conversely, users would seek out content consistent with their existing behavioral patterns.

I show that while the intervention significantly reduced user exposure to toxic content, there was an increase in the proportion of toxic posts shared. I developed a structural model to rationalize these results, so that different types of users formally respond to the intervention in heterogeneous ways. The model decomposes the total effect of the intervention into two components: change in engagement with the platform, and change in the type of content viewed. I find that while more than 80% of the behavioral response is due to changes in engagement, the remaining 20% is attributed to the influence of the content viewed.

This paper analyzed the effects of a specific algorithm on a specific platform. These results are generalizable to other platforms, to the extent that they use similar algorithms to personalize content. Further, the current analysis is restricted to the effects of the ‘random algorithm’ for one month only. Future work will focus on understanding the long-term effects of the intervention, using administrative data for later months, and survey data for 8,000 users who were part of the experiment. The broader implications of this intervention, on mental health outcomes and digital addiction, are also important to study, but were outside the scope of this paper. I aim to contribute to these strands of knowledge in future research.

My findings have important implications for policy makers looking to regulate platforms that employ new, and seemingly opaque technologies. This is because the total effect of an intervention that decreases user exposure to toxic content is, in part, determined by behavioral responses of users. Therefore, any technological regulations that stipulate that a problematic piece of content be removed from social media must necessarily take into account these behavioral effects. This would help in estimating the difference between intended and actual effects of the policy, before it is implemented.

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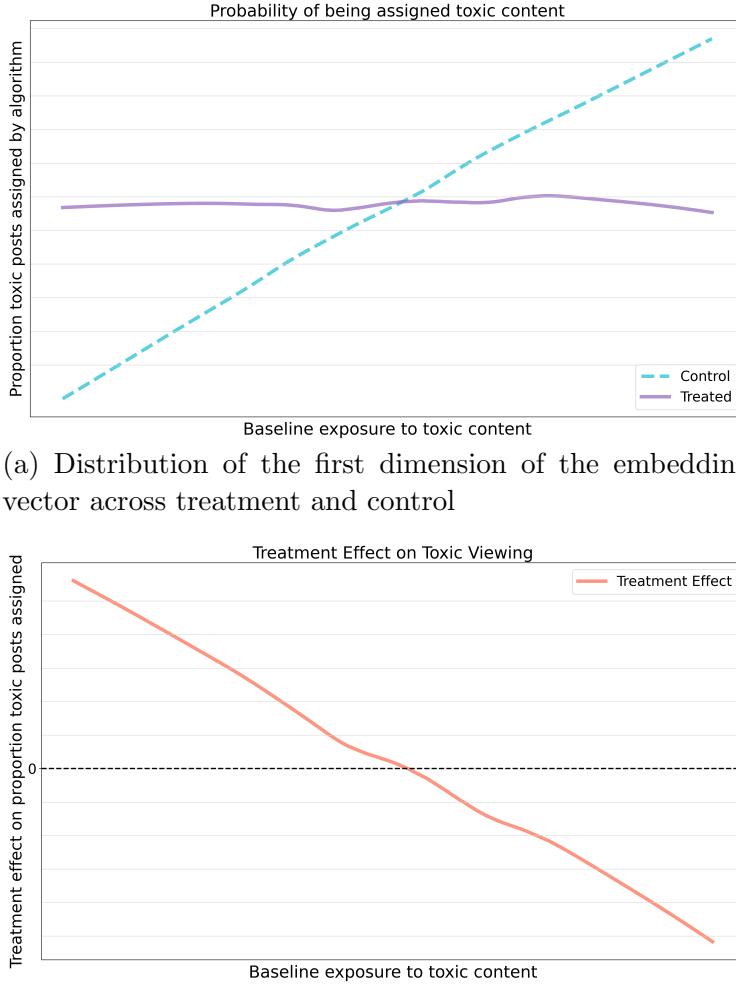
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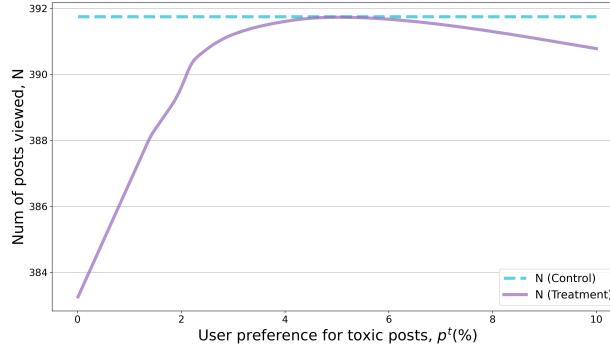
Tables and Figures

Figure 1: Example of correlation between simulated user preferences and recommendations from a simulated personalization algorithm

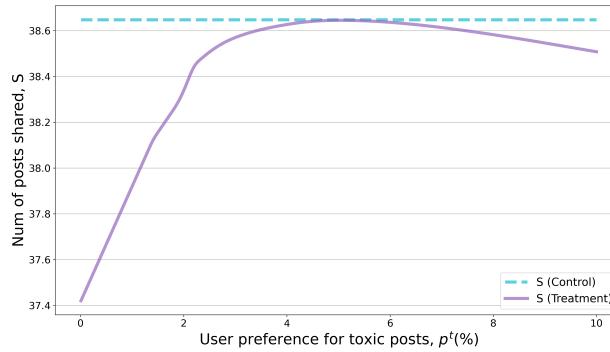


Notes: This Figure shows that there is a positive correlation between the user preferences (measured using embedding vectors at baseline), with the type of posts recommended by a simple personalization algorithm. The algorithm used to simulate the embeddings for both treatment and control groups uses Singular Value Decomposition to factorize a simulated matrix of engagement. This generates two-dimensional embedding vectors for each user and each post, where each dimension users' preference weights on different post attributes, e.g. tragedy, toxicity, comedy, etc. To fix ideas, this graph shows the first dimension of the embedding vector, which represents the toxicity of the post (as an example). In breaking this correlation between user preferences and the preferred content, treatment is expected to have a smaller effect (in absolute terms) on users with embeddings closer to the average, at baseline. This is because the treatment algorithm assigns toxic content with the average probability in the control group, as the treated users are simply assigned the average control embedding (as shown by the flat curve in panel (a)). On the other hand, users with more extreme preferences had bigger absolute effects in content exposure. Embeddings from the treatment group were uniformly drawn from an epsilon ball centered around the mean control embedding. Therefore, the embedding values for the control users form an upward sloping curve, with respect to user preferences for toxic content (which is the first dimension of the embedding vector). There is no correlation between the user embeddings in the treated groups, and users baseline embeddings, by design of the experiment. Details of the simulated personalization algorithm, and the intervention's random algorithm, are in Appendix I.

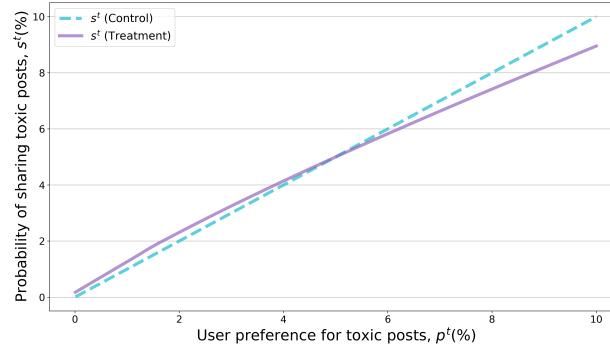
Figure 2: Model predictions, by user type or tastes for toxic content, p^t



(a) Total number of posts viewed



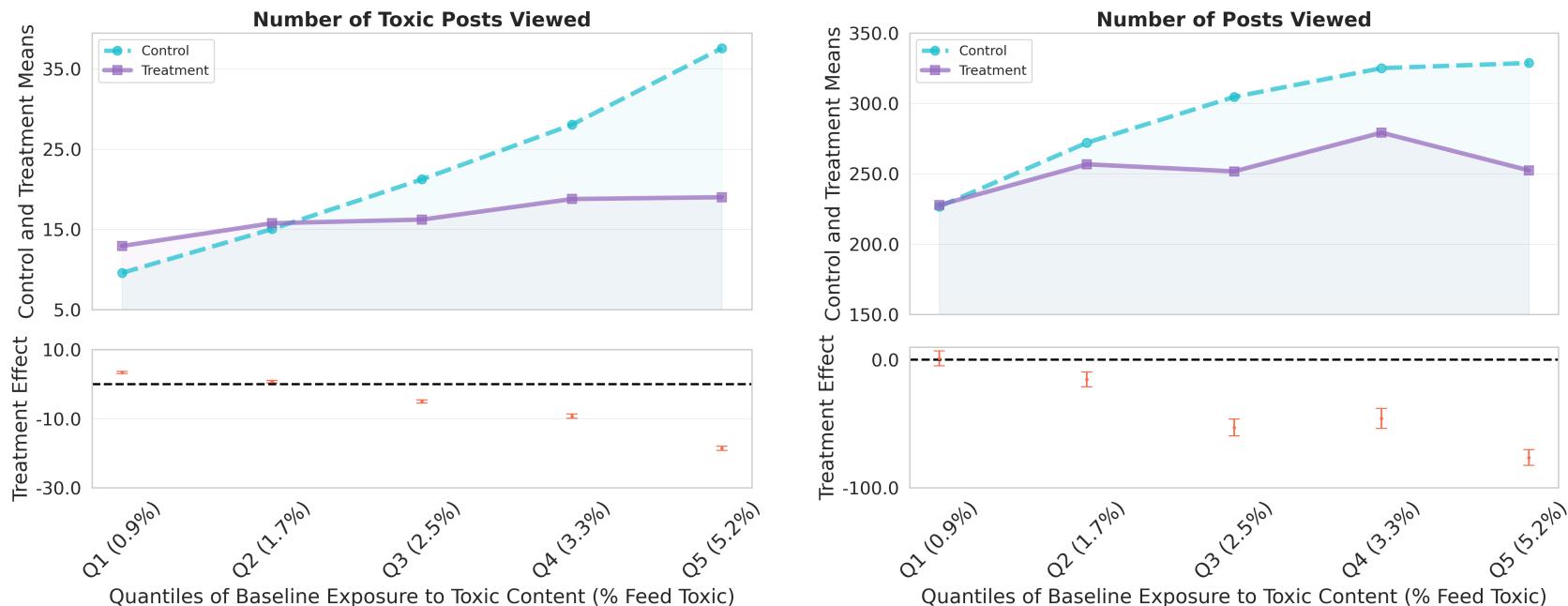
(b) Total number of posts shared



(c) Proportion of shares that are toxic

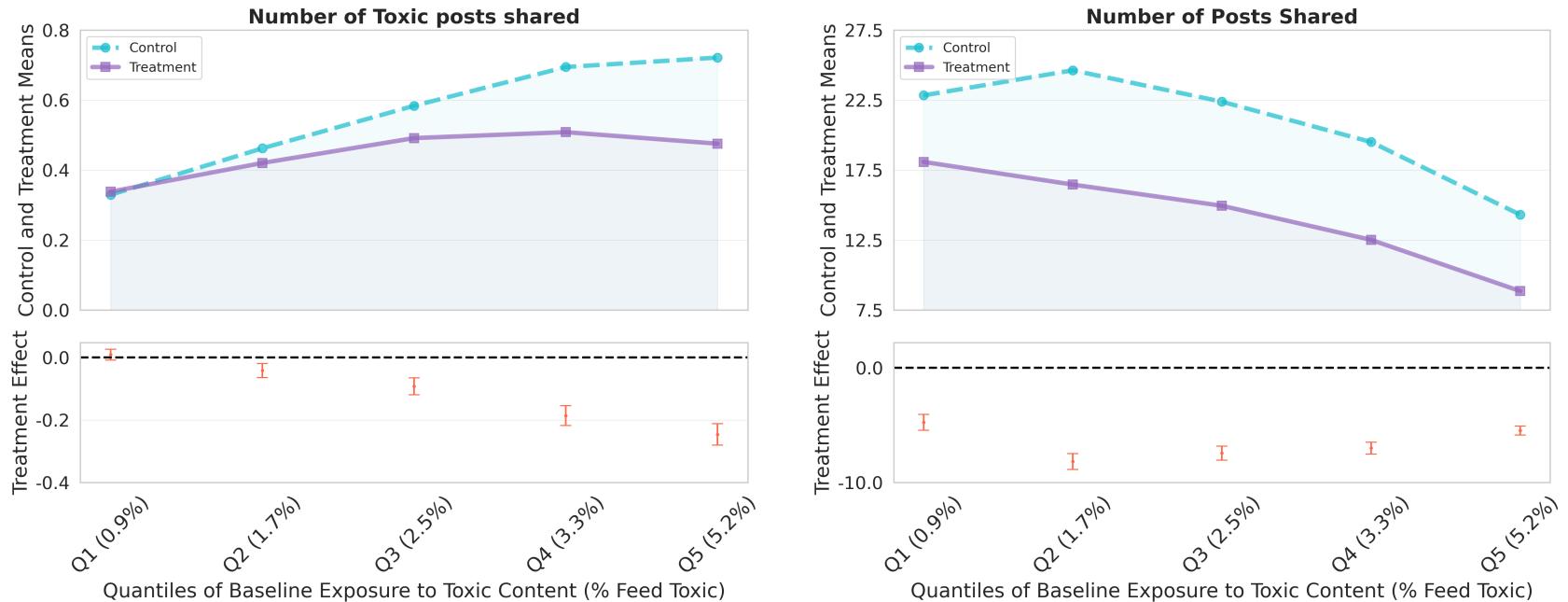
Notes: This graph provides the model's predictions for key outcomes, for different types of users, where user type is defined by user tastes for toxic content, p^t . Panels (a) and (b) show that more toxic users (towards the extreme right in the p^t distribution) are expected to view and share smaller number of posts upon being treated. Panel (c) shows that users with lower proclivity to toxic content, in the treated group, are predicted to share toxic content with higher probabilities. This means the main reduced form result that the average treatment effect on the proportion of posts shared that are toxic is positive, is driven by non-toxic users. The Figure shows that the treatment effect on the proportion of shares that are toxic is expected to be negative for toxic users, due to two reasons: (1) the reduction in total usage of the platform is larger for toxic users, and (2) behavioral changes in the probability of sharing toxic content, due to reduced exposure to such content. These predictions are obtained using calibrated parameters from the structural model, by matching moment conditions for heterogeneous users. Note that, for homogenous parameter values for users with different preferences, this model generates symmetric predictions for the number of posts viewed and shared. This is addressed later using different influence factors θ , for different user types.

Figure 3: Treatment effects on viewing behavior, by user type



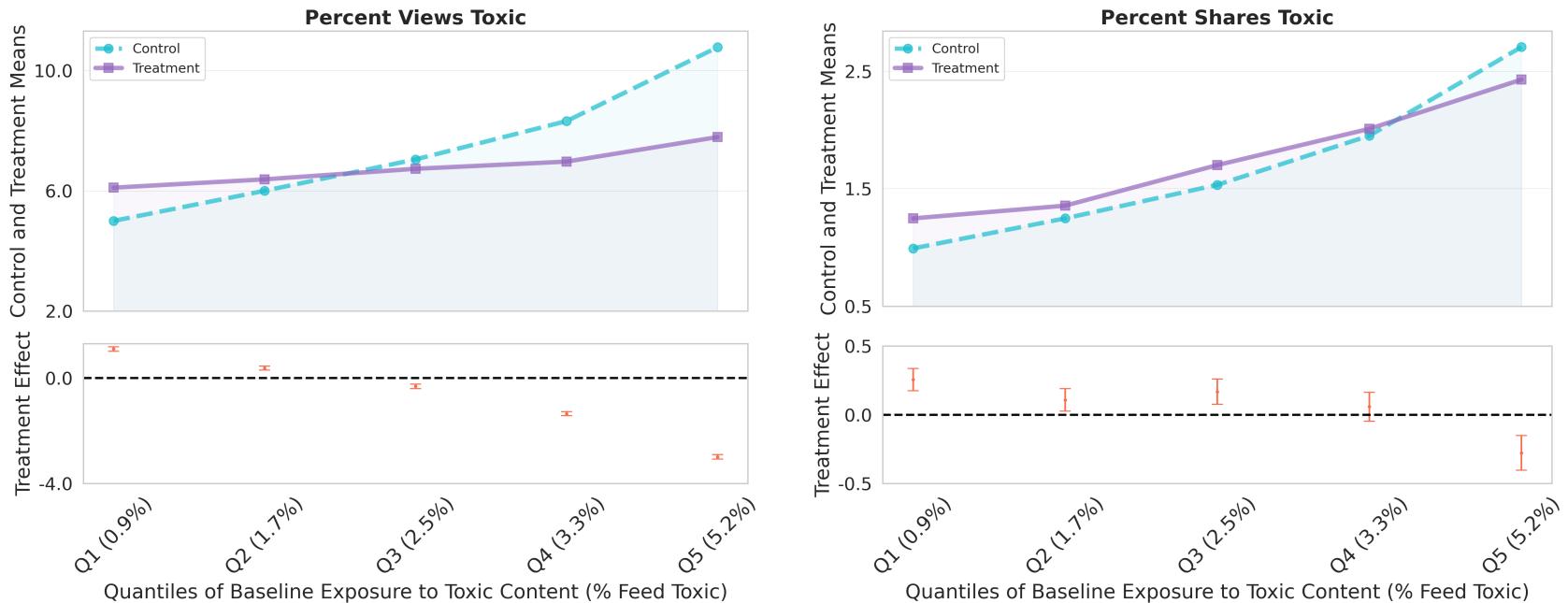
Notes: This figure shows that the treatment effect on the number of toxic posts viewed is monotonically decreasing in the exposure to toxic posts at baseline. The model formally characterized user types by the proportion of toxic posts viewed at baseline, and predicted that the treatment effect on the number of toxic posts viewed is negative and larger (in absolute terms) for toxic users. As expected, this effect is positive for users in Q1, and negative for users in Q5. However, this is not mechanically true, because the total number of posts viewed also changes by treatment status and user type, in the second panel. In fact, the treatment effect on the total number of posts viewed is larger (in absolute terms) for more toxic users. This is because of lower exposure to toxic content, and the disengagement effect. The axis corresponding to the bottom plots show the magnitude of treatment effects (as coefficient plots), while the top panel is scaled according to the control mean of the outcomes for each quantile. All regressions were run at the user level, and inference about the treatment effects is based on robust standard errors.

Figure 4: Treatment effects on sharing behavior, by user type



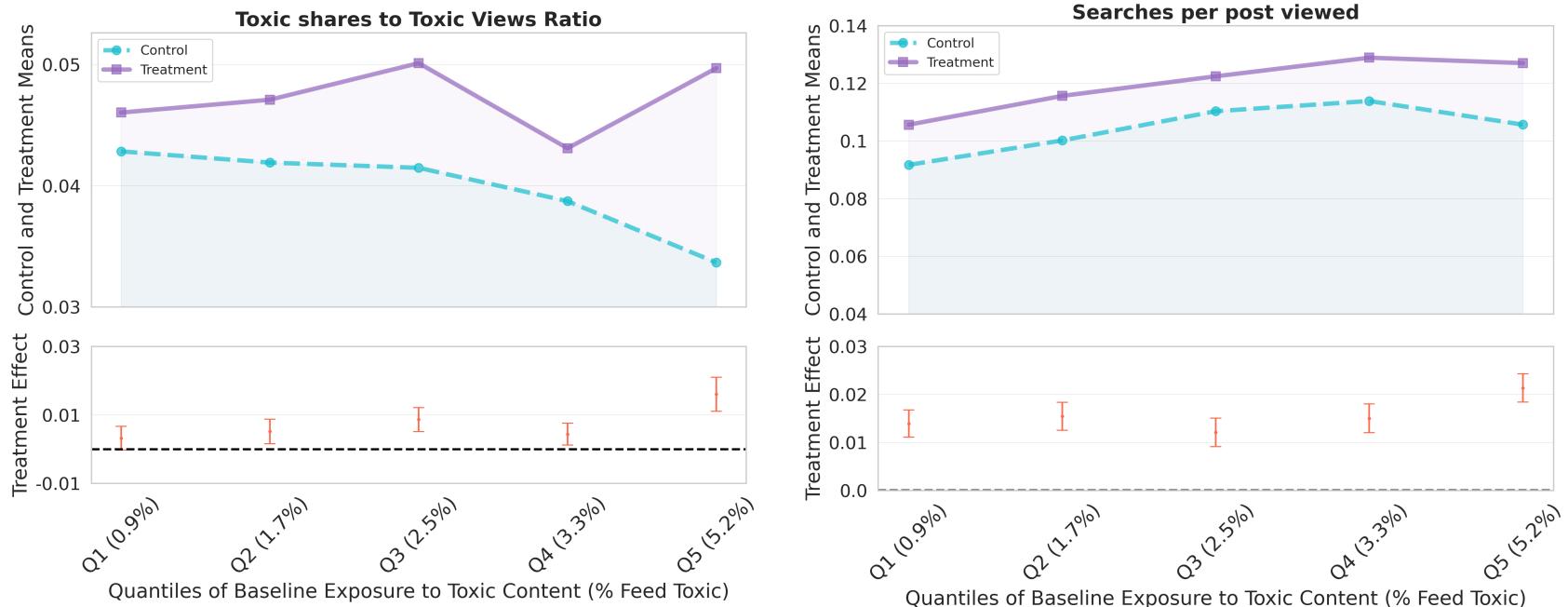
Notes: This Figure shows that the treatment effect on the number of toxic posts shared is negative for toxic users (Q3 to Q5), but is statistically insignificant (yet, positive) for users in Q1. This shows that even as there is a decrease in the number of toxic posts shared by toxic users, these users disengage with the platform by sharing fewer posts overall. From this Figure, it is therefore unclear if toxic users share fewer toxic posts because they are exposed to less toxic content they can share, they are influenced by the non-toxic content they are exposed to, or they are disengaging with the platform. Overall, the proportion of shares that are toxic is positive, despite big reductions in the number of toxic posts shared. The axis corresponding to the bottom plots show the magnitude of treatment effects (as coefficient plots), while the top panel is scaled according to the control mean of the outcomes for each quantile. All regressions were run at the user level, and inference about the treatment effects is based on robust standard errors.

Figure 5: Treatment effects on toxic behavior, by user type



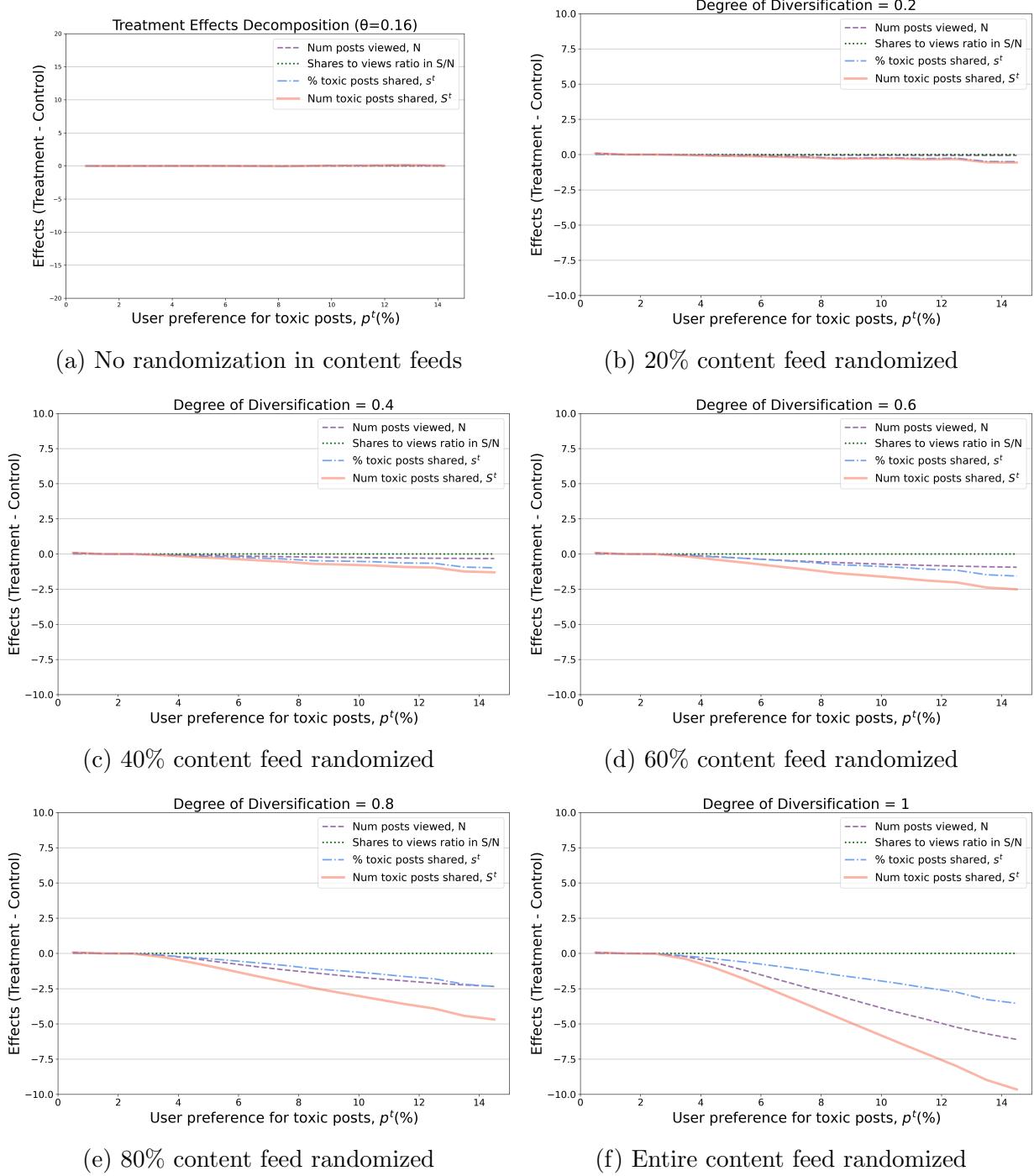
Notes: This figure shows that the treatment effect, on the *proportion* of posts shared that are toxic, is *non-negative* for all users except those in Q5 (with the highest exposure to toxic content at baseline). This is true, even in the cases of Q3 to Q5, where user type is toxic enough that the treatment effect on toxic views is negative (left panel). The model predicts positive treatment effect on the proportion of toxic shares for users with lower degree of proclivity to toxic content, but decreased overall engagement with the platform from more toxic users. On average, the ratio of toxic shares to toxic views is higher among the treated, and this is likely driven by users with low to medium proclivity to toxic content. The axis corresponding to the bottom plots show the magnitude of treatment effects (as coefficient plots), while the top panel is scaled according to the control mean of the outcomes for each quantile. All regressions were run at the user level, and inference about the treatment effects is based on robust standard errors.

Figure 6: Complimentary evidence on seeking out behavior, by user type



Notes: This figure provides complimentary evidence explaining the ‘stickiness’ in user behavior. User behavior is not malleable, because the ratio of toxic shares to toxic views is always less than 1 for all user types, across treatment and control groups. This means that user behavior is only partly influenced by the content they are exposed to, and this influence is quantified using the structural model. The first panel also suggests that toxic users are more malleable, while non-toxic users are mechanical, because there is no change in the proportion of toxic sharing to toxic viewing. The second panel shows that the treatment effect on the ratio of searches to views was positive and higher for users with higher toxic exposure at baseline. That is, toxic users were more likely to seek out content in the time they spent on the platform, by using the ‘text search’ feature. The axis corresponding to the bottom plots show the magnitude of treatment effects (as coefficient plots), while the top panel is scaled according to the control mean of the outcomes for each quantile. All regressions were run at the user level, and inference about the treatment effects is based on robust standard errors.

Figure 7: Counterfactual policy predictions for different levels of randomization in content feeds



Notes: This Figure simulates the counterfactual policy predictions for different levels of randomization in content feeds. The different degrees of randomization are achieved by considering linear combinations of the probabilities of being assigned toxic content in the control and treatment groups. That is, the counterfactual probabilities of being assigned toxic content under different policy regimes is given by $q_i^{t,a} = a \cdot q^t + (1 - a) \cdot q_i^t$. This shows that a policy when $a = 60\%$, the decrease in the number of toxic posts is driven by the decrease in the probability of being assigned toxic content for toxic users. This is ideal for a policymaker who wants to reduce the number of toxic posts viewed and shared, without affecting the overall engagement of the platform. However, as the degree of randomization increases to 80%, decrease in engagement by toxic users contributes more to the decrease in the number of toxic posts shared. Therefore, the policymaker can choose the degree of randomization, a , to balance this trade-off between reducing toxic engagement and overall engagement with the platform.

Table 1: Structural estimation of influence parameter θ , with measurement error correction

	(1) Difference in Toxic and non-Toxic Views (Baseline, half-2)	(2) Difference in Toxic Shares (Intervention - Baseline)	(3)
Difference in Toxic and non-Toxic Views (Baseline, half-1)	0.572*** (0.004)	-0.155** (0.0580)	
Difference in Toxic and non-Toxic Views (Baseline)			-0.183** (0.0652)
N	63041	63041	63041

Notes: This Table provides estimates for the structural parameter θ in the model of sharing behavior, where θ captures the rate at which users update behavior, according to the perceived social norms. θ is, therefore, the influence effect of one month's exposure to non-personalized feeds. This is modelled as the extent to which users share content to signal their conformity with the behavior of other users in their network, to derive benefits of public recognition. Column (1) shows relevance of the instrument, i.e. the differences between probability of viewing toxic and non-toxic content, computed using only the first half of posts viewed by user at baseline, when they were arranged in a random order (*half1*). This instrument is used to correct the measurement error, on account of treated users randomly sampling toxic posts to view from their feeds. The independent variable in Column (1) is the difference between proportion of toxic and non-toxic posts viewed at baseline, computed using only the second half of posts viewed by a user at baseline, when they were arranged in a random order (*half2*). Column (2) shows results of a 2SLS regression of the difference between baseline and intervention period in differences between probability of *sharing* toxic and non-toxic content. Here, the independent variable is *half1*, which was instrumented with *half2*. Column (3) estimates the model with classical measurement error correction in STATA, where the correlation between *half1* and *half2* serves as the reliability measure for the proportion of toxic posts viewed. Estimated slope coefficient estimates γ_1 is always negative and statistically significant. Estimated θ is therefore, positive, and estimated to be 0.16, according to the preferred specification in Column (2). Baseline period is December, 2022 and intervention period data spans from February 10, 2023 and March 10, 2023. Robust standard errors are in parentheses. $p < .0001^{***}$, $p < .01^{**}$, $p < .05^*$.

Table 2: Experimental Effects on Post Views and Shares

	Num Posts Viewed	Num Posts Shared
Treatment Effect	-35.497** (2.208)	-6.367** (0.206)
Control Mean	246.654** (1.361)	18.396** (0.131)
	Num Toxic Posts Viewed	Num Toxic Posts Shared
Treatment Effect	-5.024** (0.172)	-0.093** (0.010)
Control Mean	18.806** (0.129)	0.474** (0.006)
	% Toxic Posts Viewed	% Toxic Posts Shared
Treatment Effect	-0.641** (0.033)	0.120** (0.038)
Control Mean	7.416** (0.018)	1.547** (0.018)
N	231814	

Notes: This table shows that the treatment effect on the number of posts viewed and shared, as well as the number of toxic posts viewed and shared, in one month, is negative and statistically significant. Each cell reports estimates of the regression coefficient from a linear regression of the outcome aggregated at the user level, over days in the first month of the intervention period (February 10 to March 10, 2023). Robust standard errors are in parentheses. $p < .0001^{***}$, $p < .01^{**}$, $p < .05^*$.

A Details of Behavioral Model

This theoretical framework outlines users' incentives to view and share different types of content. That is, (1) users have some innate tastes for toxic content, and (2) they want to signal their type to conform with society's tastes (as perceived by the user). Users are assumed to update their perception of norms based on the content they view, and the algorithm in turn internalizes distortions from users' desire to conform to social norms.

A.1 Timing

First, nature randomly assigns user specific parameters $\{\alpha, \beta, p^t, \theta\}$. These parameters not only reflect how a user values consumption of different types of content, but also how she values conformity with peers. That is, nature assigns user tastes for viewing and sharing, β and α respectively. The utility weight user places on conforming with social norms, i.e. θ , is also realized. Later, I show that θ is effectively the rate at which users update their behavior or are influenced by the content they view.

Second, the platform optimizes its ad-revenue by algorithmically assigning content that users are more likely to stay and engage with. Assuming there are two types of posts on the platform, toxic and non-toxic, the algorithms' choice variable in this model is q^t only, with $q^n = (1 - q^t)$. The algorithm chooses these probabilities to maximize the total number of posts viewed by each user, N . Next, for the given assignment probabilities, the user decides the total number of posts she will view N , or the total time she will spend on the platform upon observing the assignment probabilities. The user is thought to learn the distribution of content recommendations that the algorithm would make, so that the choice of N determines the expected number of posts of each type that she views.

The user responds to the realization of the number of toxic and non-toxic posts viewed, through her engagement behavior, i.e. by sharing a viewed post. That is, the user chooses the total number of posts to share, S , which offers the user with some consumption utility, and also scales the behavioral response. Finally, the user chooses the fraction of shared posts that are toxic, $s^t = S^t/S$, in order to maximize utility, for given exposure and sharing decision.

A.2 Equilibrium

I solve for the subgame perfect equilibrium, and introduce user (i) and time (τ) subscripts. All four stages of the game are assumed to be played in sequence, in both the time periods, $\tau = 0$ (baseline) and $\tau = 1$ (intervention period). By backward induction, users first maximize utility by choosing the total number of posts to share, and also the number of toxic posts to share, i.e. $S_{i,\tau}$ and $S_{i,\tau}^t$, respectively. Users' best response characterizes one of the main outcome variables, i.e. proportion of toxic posts to share, $s_{i,\tau}^t = S_{i,\tau}^t/S_{i,\tau}$.

Lemma A.1. *For a utility maximizing agent i ,*

$$s_{i,\tau}^t = (q_{i,\tau}^t)^\theta (p_i^t)^{1-\theta} \quad (8)$$

That is, users place a weight of θ social norms, as perceived by the user through her feed, while choosing the proportion of posts shared that are toxic.

Proof. The claims follow from users' first order condition (with respect to $s_{i,\tau}^r$) from the utility maximization problem stated above in (??). \square

The optimal sharing strategy is a combination of user's own tastes and the content she is shown, $q_{i,\tau}^t$, weighted by $(1 - \theta)$ and θ , respectively. The distribution of toxic posts on a user's content feed informs her about the type of content that a similar user is engaging with, and is therefore, socially acceptable. She values conformity with these perceived norms according to some factor θ . Otherwise, sharing decisions are made according to the user's own immutable tastes for toxic content, p_i^t . The user also decides the number of non-toxic posts she will share, if any, upon viewing posts in their feed.

Lemma A.2. *For a utility maximizing agent i ,*

$$S_{i,\tau} = \frac{1}{2(\eta + \alpha)} [2N_{i,\tau}\alpha - \delta\theta(1 - \theta)((\log p_i^t)^2 - 2\log q_{i,\tau}^t \log p_i^t + (\log q_{i,\tau}^t)^2)] \quad (9)$$

That is, total number of posts shared is higher for more engaged users, with higher $N_{i,\tau}$; but is decreasing in the cost of sharing, η and the cost of viewing content that is not shareable, α .

Proof. The SPE's are solved for using backward induction. This follows from the first order condition of the user's utility maximization problem, after substituting optimal $s_{i,\tau}^t$ in the utility function. \square

The number of posts shared seems to be increasing in user's own taste for toxic content, p_i^t , as well as their perception of society's tastes, conveyed by $q_{i,\tau}^t$. However, the correct comparative statics with respect to $S_{i,\tau}$ take into account the fact that total shares depend on the endogenous response to the total number of posts viewed N . Then, a forward-looking rational user i solves for the total number of posts to view, N , or the total time she spends on the platform looking at posts.

Lemma A.3. *For a utility maximizing agent i ,*

$$N_{i,\tau} = \frac{1}{2\alpha\eta} \left[\beta(\alpha + \eta) - \delta\alpha\theta(1 - \theta) \left(\log \frac{q_{i,\tau}^t}{p_i^t} \right)^2 \right] \quad (10)$$

That is, users view a smaller number of posts when there is a mismatch between their preferences and the algorithmically generated preferences, $q_{i,\tau}^t \neq p_i^t$.

Proof. I begin by substituting the optimal sharing behavior (from Lemmas A.1 and A.2) into the utility function. User's first order condition, with respect to the total number of posts viewed generates the required expression. This shows that $N_{i,\tau}$ is decreasing in $\left(\log \frac{q_{i,\tau}^t}{p_i^t} \right)^2 > 0$. Therefore, $N_{i,\tau}$ is maximized when $q_{i,\tau}^t = p_i^t$. \square

This clearly shows that when users are assigned content randomly, they are likely to spend less time on the platform. This is because the recommendations do not match user

preferences, as extreme reated users are recommended the average user's feed. Lemma ?? describes the total number of posts viewed in terms of the model's primitives. Subsequently, $N_{i,\tau}^t$ in equilibrium helps in determining the total number of posts shared, $S_{i,\tau}$. The given utility form provides two solutions for the total number of posts shared, one of which is zero. I describe the non-zero solution in terms of model primitives.

Lemma A.4. *For a utility maximizing agent i ,*

$$S_{i,\tau} = \frac{1}{2\eta} \left[\beta - \delta\theta(1-\theta) \left(\log \frac{q_{i,\tau}^t}{p_i^t} \right)^2 \right] \quad (11)$$

That is, users share a smaller number of posts when there is a mismatch between their preferences and the algorithmically generated preferences, $q_{i,\tau}^t \neq p_i^t$.

Proof. This expression is obtained by substituting (10) into the optimal sharing function in (11). This shows that $S_{i,\tau}$ is decreasing in $\left(\log \frac{q_{i,\tau}^t}{p_i^t} \right)^2 > 0$. Therefore, $S_{i,\tau}$ is maximized when $q_{i,\tau}^t = p_i^t$. \square

The solution to the user's problem is therefore, fully characterized for the given probability of being assigned toxic content, $q_{i,\tau}^t$. For the given timing of the game, I finish characterizing the equilibrium by solving for the algorithm's optimal assignment probabilities. The platform's customization algorithm is trained to maximize the expected number of posts viewed in order to increase eyeballs on advertisement posts that are interspersed on the users' ranked content feed. Therefore, the platform feeds the objective function in (10) to the algorithm, which in turn optimally chooses $q_{i,\tau}^t$ to maximize advertisement revenues.

Lemma A.5.

$$q_{i,\tau}^t = p_i^t \quad (12)$$

That is, the algorithm assigns toxic posts with probability equal to user's intrinsic tastes for toxic content.

Proof. This follows directly from the first order conditions of an algorithm that is set to maximize $N_{i,\tau}$ in (10), by choosing $q_{i,\tau}^t$ optimally. The same result follows if the algorithm's objective is defined more broadly, choosing $q_{i,\tau}^t$ to maximize $N_{i,\tau}^t$, or $S_{i,\tau}^t$, or some linear combination of the two. This is because the number of posts viewed and shared is decreasing in $\left(\log \frac{q_{i,\tau}^t}{p_i^t} \right)^2 \geq 0$, which equals zero when $q_{i,\tau}^t = p_i^t$. \square

Recall that the assignment probabilities provide a heuristic for the algorithm, that provides an intuitive explanation for what the algorithm actually does. This intuitive result shows that the algorithm caters to users' intrinsic tastes for viewing toxic content. The algorithm internalizes users' incentives to signal their type and their conformity, but in equilibrium the algorithm assigns toxic content according to user's intrinsic tastes.⁴⁵ The result

⁴⁵That is, the algorithm enables the self-fulfilling prophecy characteristic of statistical discrimination models, where user types determine the type of content users are assigned, and users share these posts to in turn, signal their type (Coate and Loury, 1993).

provides concrete basis to analyze behavior according to user type, where types are characterized according to the proportion of toxic posts assigned to them at baseline. This is because, in the equilibrium at baseline, the assignment probabilities are necessarily equal to user's intrinsic tastes for toxic content. The model provides comparative statics, that generate implications tested in the data.

B Proofs for Theoretical Framework

B.1 Proof of Proposition 1

For user i with $\alpha, \eta, N_{i,\tau} > 0$, and $p_i^t > \bar{q}^t$,

$$\frac{\partial^2 N_{i,\tau}}{\partial p_i^t \partial \bar{q}^t} \geq 0$$

That is, the reduction in the total number of posts viewed, on account of the treatment, is larger for users with higher proclivity to toxic content.

Proof. Lemma A.3 implies

$$N_{i,\tau} = \frac{1}{2\alpha\eta} \left[\beta(\eta + \alpha) - \delta\alpha\theta(1 - \theta) \left(\log \frac{q_{i,\tau}^t}{p_i^t} \right)^2 \right]$$

With random content assignment during the intervention period (\bar{q}^t),

$$\frac{\partial N_{i,\tau}}{\partial \bar{q}^t} = \frac{-1}{2\alpha\eta} \left[\frac{2}{\bar{q}^t} \delta\alpha\theta(1 - \theta) \log \frac{\bar{q}^t}{p_i^t} \right]$$

Note that, $p_i^t > \bar{q}^t$ is both necessary and sufficient for the derivative to be positive. That is, for users with higher proclivity to toxic content, randomly increasing the probability of assigning such content increases the number of posts viewed. Consider, the cross derivative with respect user tastes, p_i^t gives,

$$\frac{\partial^2 N_{i,\tau}}{\partial p_i^t \partial \bar{q}^t} = \frac{1}{2\alpha\eta} \left[\frac{2}{\bar{q}^t p_i^t} \delta\alpha\theta(1 - \theta) \right] \geq 0$$

because $\theta \in [0, 1]$, $\bar{q}^t, p_i^t \in (0, 1)$, and $\alpha, \eta, \beta, \delta > 0$.

Then, for $p_i^t > \bar{q}^t$, random increases in probability of assigning toxic content increases the number of posts viewed, and the increase is larger for more toxic users. Conversely, when exogenous reductions in \bar{q}^t decrease the number of posts viewed for toxic users, the reduction is larger for more toxic users. \square

B.2 Proof of Proposition 2

For user i with $\alpha, \eta, S_{i,\tau} > 0$, and $p_i^t > \bar{q}^t$,

$$\frac{\partial^2 S_{i,\tau}}{\partial p_i^t \partial \bar{q}^t} \geq 0$$

That is, the treatment effect on the total number of posts shared is larger for users with higher proclivity to toxic content.

Proof. Lemma A.4 implies

$$S_{i,\tau} = \frac{1}{2\eta} \left[\beta - \delta\theta(1-\theta) \left(\log \frac{\bar{q}^t}{p_i^t} \right) \right]$$

For users with higher proclivity to toxic content, i.e. $p_i^t > \bar{q}^t$, the treatment leads to exogenous increases lead to increases in the number of posts shared, because

$$\frac{\partial S_{i,\tau}}{\partial \bar{q}^t} - \frac{\delta\theta(1-\theta)}{\eta \bar{q}^t} \log \left(\frac{\bar{q}^t}{p_i^t} \right) \geq 0$$

when $p_i^t > \bar{q}^t$, because $\log(x) < 0$ for $x \in (0, 1)$. Then, the cross derivative with respect to user tastes, p_i^t gives,

$$\frac{\partial^2 S_{i,\tau}}{\partial p_i^t \partial \bar{q}^t} = \frac{\delta\theta(1-\theta)}{\eta \bar{q}^t p_i^t} \geq 0$$

for $\bar{q}^t, p_i^t \in (0, 1)$, $\theta \in [0, 1]$ and $\alpha, \eta, \beta, \delta > 0$. \square

B.3 Proof of Proposition 3

For user i with $\eta, N_{i,\tau}, S_{i,\tau} > 0$,

$$\frac{\partial^2 s_{i,\tau}^t}{\partial p_i^t \partial \bar{q}^t} \geq 0$$

That is, the treatment effect on the proportion of toxic posts shared is negative and smaller for users with higher proclivity to toxic content.

Proof. From Lemma A.1 shows that,

$$s_{i,\tau}^t = (q_{i,\tau}^t)^\theta (p_i^t)^{1-\theta}$$

Then, we can see that

$$\frac{\partial^2 s_{i,\tau}^t}{\partial p_i^t \partial \bar{q}^t} = \theta(1-\theta) (q_{i,\tau}^t)^{\theta-1} (p_i^t)^{-\theta} \geq 0$$

for $\theta \in [0, 1]$, and $q_{i,\tau}^t, p_i^t \in (0, 1)$. \square

B.4 Proof of Proposition 4

User i with $N_{i,\tau}, S_{i,\tau} > 0$, is said to behave ‘mechanically’ when $\theta = \beta = \eta = 0$. That is, when $\theta = \beta = \eta = 0$, the elasticity of the proportion of toxic posts shared with the respect to the proportion of toxic posts viewed is 1.

Proof. If, $\theta = 0$, the utility maximization problem becomes,

$$\max_{s^t, S, N} = \alpha(N - S)^2 - \delta S \left(\log \frac{q^t}{p^t} \right)^2 - \eta S^2 \quad (13)$$

Utility is maximized with respect to s^t when $s_{i,\tau}^t = p_i^t$. Then, by definition,

$$\frac{S_{i,\tau}^t}{S_{i,\tau}} = s_{i,\tau}^t = p_i^t$$

We know that in equilibrium, $q_{i,\tau} = p^t$. Then, assuming users view all the posts they are assigned, i.e. $\beta = 0$, we have, $N_{i,\tau}^t = q_{i,\tau}^t N$. Therefore,

$$\frac{S_{i,\tau}^t}{S_{i,\tau}} = \frac{N_{i,\tau}^t}{N_{i,\tau}} = p_i^t = q_{i,\tau}^t \quad (14)$$

Then the treatment implies that,

$$\frac{\partial s_{i,\tau}^t}{\partial \bar{q}^t} = \frac{\partial v_{i,\tau}^t}{\partial \bar{q}^t} = 1 \quad (15)$$

where, $v_{i,\tau}^t = \frac{N_{i,\tau}^t}{N_{i,\tau}}$, and, elasticity of toxic sharing with respect to toxic viewing is

$$\frac{\partial s_{i,\tau}^t / \partial \bar{q}^t}{\partial v_{i,\tau}^t / \partial \bar{q}^t} = 1$$

□

B.5 Proof of Lemma 1

Estimates of θ from the relationship between sharing behavior and the proportion of toxic content viewed during the intervention period among a sample of control users is not identified.

Proof. Consider the linear structural relationship,

$$\log s_{i,1}^t - \log s_{i,0}^t = \theta v_{i,1}^t + \log w_i^t$$

and suppose that, *by contradiction*, θ is estimable, using control users. This necessarily implies that $E[\log w_i^t | \log v_{i,1}^t] = 0$. The steady state condition implies that the left-hand side of the equation is always zero, meaning

$$E[\log s_{i,1}^t - \log s_{i,0}^t | \log v_{i,1}^t] = 0$$

This implies that $\theta = 0$. However, this contradicts Proposition 4 which shows that $\theta > 0$. Therefore, θ is not estimable from this relationship, in the sample of control users. □

B.6 Proof of Proposition 6

For some updating parameter θ , and treated user i , the change in ratio of toxic-shares to non-toxic shares from the baseline is a function of the log-odds ratio of the proportion toxic posts viewed at baseline. That is,

$$\log \left(\frac{s_{i,1}^t}{s_{i,1}^n} \right) - \log \left(\frac{s_{i,0}^t}{s_{i,0}^n} \right) = (1 + \theta) \log \left(\frac{\bar{q}^t}{\bar{q}^n} \right) - \theta \log \left(\frac{v_{i,0}^t}{v_{i,0}^n} \right)$$

Proof. The optimal sharing function for treated users is given by

$$s_{i,1}^t = (v_{i,1}^t(\bar{q}^t))^{\theta} (w_i^t)^{\mu} (s_{i,0}^t)^{1-\theta} \quad (16)$$

$$s_{i,1}^n = (v_{i,1}^n(\bar{q}^n))^{\theta} (w_i^n)^{\mu} (s_{i,0}^n)^{1-\theta} \quad (17)$$

The steady state condition is

$$s_{i,0}^t(v_{i,0}^t, w_i^t) = s_{i,1}^t(v_{i,1}^t(q_{i,1}^t), s_{i,0}^t, w_i^t) \quad (18)$$

$$s_{i,0}^n(v_{i,0}^n, w_i^n) = s_{i,1}^n(v_{i,1}^n(q_{i,1}^n), s_{i,0}^n, w_i^n) \quad (19)$$

This simplifies to

$$s_{i,0}^t = (v_{i,0}^t)(w_i^t)^{\frac{\mu}{\theta}} \quad (20)$$

$$s_{i,0}^n = (v_{i,0}^n)(w_i^n)^{\frac{\mu}{\theta}} \quad (21)$$

By design of the experiment, the treated users view a constant proportion of toxic content during the intervention period. Reiterating,

$$v_{i,1}^t = \bar{q}^t \quad \text{and} \quad v_{i,1}^n = \bar{q}^n \quad (22)$$

Then, define $\log \left(\frac{s_{i,1}^t}{s_{i,1}^n} \right)$ as the log-odds of sharing toxic content. Plugging values from (16), (20) and (22) into the definition of the log-odds ratio of sharing toxic content in (??), so that

$$\log \left(\frac{s_{i,1}^t(1)}{s_{i,1}^n(1)} \right) - \log \left(\frac{s_{i,0}^t(1)}{s_{i,0}^n(1)} \right) = \underbrace{\theta \log \left(\frac{\bar{q}^t}{\bar{q}^n} \right)}_{\text{constant}} - \underbrace{\theta \log \left(\frac{v_{i,0}^t}{v_{i,0}^n} \right)}_{\text{by eqm. cond. (20)}}$$

which is the required expression in the stated proposition. \square

C Details of Structural Model and estimation

This Appendix provides supplementary information on the structural model that enables estimation of some key parameters of interest. First, I discuss why the setting requires a model to estimate θ , and the reasons that standard estimation strategies are not applicable.

C.1 The Necessity of Structure

Since exposure and engagement with toxic content are endogenous variables due to the personalization algorithm, the demand and supply factors that drive problematic behavior cannot be disentangled using the control group data. This is because the algorithm is trained on some underlying user preferences that also determine user behavior, but are not observed by the researcher. This is the main identification problem that the experiment solves. The experiment replaces algorithmically generated content recommendations with a random draw of posts to identify user ‘demand’ for different types of content.

However, the reduced form relationship between toxic exposure and engagement across treatment and control does not identify the main mechanism of interest: the influence of *exposure* to toxic content on engagement behavior with respect to such content. Without additional assumptions, the experimental variation cannot distinguish between the components of user behavior: innate tastes for toxic content and behavioral responses due to preference for conformity. This is because a draw of posts is picked randomly for the treated users each day, and the Law of Large Numbers implies that the average proportion of toxic posts viewed by treated users is constant over time, at the average probability of being assigned toxic content in the control group.

The random algorithm assigns content in a way that is independent of both these components of user behavior, because the assignment probabilities are drawn from the control distribution of assignment probabilities, *each day*. The Central Limit Theorem (CLT) predicts that due to these daily random draws, the probability of assigning toxic posts for the treated group converges to a normal distribution centered at the average probability of assigning toxic posts in the control group. Further, the variance of the assignment probabilities in treatment is much lower than the control (by a factor of $\sqrt{|\{i|D_i = 1\}|}$) (Hayashi, 2011). In fact, exposure to a particular type of content is almost always constant among treated users, rendering the relationship between exposure and engagement unidentifiable in a regression of engagement on exposure, in the treatment group.

The concentration of the treatment embeddings around the mean of the control embeddings is also demonstrated in a simple personalization algorithm that is trained on simulated engagement data (See Section 3 and Appendix I). I further belabor this point about the absence of a straight forward identification strategy using the reduced form relationship between toxic viewing and sharing in the treatment group. Consider a difference-in-difference estimator to identify the behavioral chain of effects from the change in toxic views because of the intervention, to the change in toxic shares

$$E \left[\log \frac{s_{i,1}^t}{s_{i,0}^t} \middle| D_i = 1 \right] - E \left[\log \frac{s_{i,1}^t}{s_{i,0}^t} \middle| D_i = 0 \right] = \theta \left(E \underbrace{\left[\log \frac{v_{i,1}^t}{v_{i,0}^t} \middle| D_i = 1 \right]}_{\text{=0 in steady state}} - E \underbrace{\left[\log \frac{v_{i,1}^t}{v_{i,0}^t} \middle| D_i = 0 \right]}_{\text{=0 in steady state}} \right)$$

where, D_i is an indicator for treatment status. This does not identify the main parameter of interest θ , because the algorithm and control users remain in steady state during the intervention period. As a result, differences in toxic views and shares from baseline for the control users is always zero. Moreover, the distribution of toxic views for treated users is constant during the intervention period, as the treatment assignment probabilities approximate the

mean in the control distribution, for each treated user. Therefore, θ is not estimable using a standard difference-in-difference approach.

The difference-in-difference estimator is also amenable to incorrect interpretation, if not correctly grounded in economic theory. The DiD specification implies that θ is the change in sharing behavior due to a change in exposure to toxic content. Suppose I incorrectly estimated the DiD estimator using the data, and found a negative coefficient (Table 3 shows this to be the case). This would imply that exposure influences behavior negatively, so that users who saw more toxic content during the intervention period shared less toxic content. However, this is not the case, as the structural model shows that the influence parameter is positive, and between zero and one.

Table 3: Faulty estimates from a difference-in-differences model

	(1)	(2)
	Avg toxicity in sharing	Total toxicity in sharing
DiD estimate	-0.041 (0.028)	0.003*** (0.001)
<i>N</i>	231814	231814

Notes: This table shows that the difference-in-differences estimate of the treatment effect on sharing toxic content is negative, although statistically insignificant. Column (1) shows the effect on the change in the average toxicity of shares, while Column (2) shows the effect on the change in the total number of toxic posts shared. Column (1) is the closest analog to the structural equation estimated, and the results in Column (2) may be biased because more toxic users may be as treated users may also change the number of non-toxic posts they share. Robust standard errors in parentheses. $p < 0.05^*, p < 0.01^{**}, p < 0.001^{***}$.

A model-free interpretation of this estimator implies that the treatment promoted a backlash against the posts treated users were randomly exposed to. The model provides an estimator for the effect of content exposure that is generalizable to all users, by using exposure to toxic content among treated users at *baseline only*. This enables an interpretation of the mechanisms driving the treatment effects, as the model of behavior below is well identified and accounts for unobserved heterogeneity across users. I distinguish between two channels that drive the treatment effect of switching off the content recommendation algorithms: **(1)** users' innate tastes for problematic content (measured by baseline shares), weighted by $1 - \theta$, **(2)** influence of users' perception of society's preferences (measured by toxic exposure), weighted by θ .

C.2 Estimation

I estimate the updating parameter θ from the relationship between baseline exposure to toxic content ($v_{i,0}^t$), and the odds of sharing toxic content during the intervention period ($s_{i,1}^t / s_{i,1}^n$) among *treated* users only. This measures the degree of malleability of user behavior, in the face of algorithm's content recommendations. θ is estimated in a linear regression due to the absence of correlation between toxic views in the pre-intervention period and those during the intervention period among treated users, as shown above. However, notice that

regression with logs is not independent of the units of measurement, and the presence of zeroes in the data can generate misleading results (Thakral and Tô, 2023). Further, adding a small constant to the logs that may generate estimates that can be incorrectly interpreted (Chen and Roth, 2023).

I approximate the log-ratios in Proposition 6 with first differences to estimate θ using a Taylor Series approximation (Abbott et al., 2001). Define, $A_{i,\tau} = v_{i,\tau}^t - v_{i,\tau}^n$ and $B_{i,\tau} = s_{i,\tau}^t - s_{i,\tau}^n$. Further, $\Delta B_{i,\tau} = B_{i,\tau} - B_{i,\tau-1}$. Then, the following procedure states the estimation strategy implemented in the data.

Proposition 7. *The behavioral effect of exposure, θ is identified in a linear model of treated users responding to exposure to toxic content if*

(SA1) *treated users update their beliefs and sharing behavior in accordance with exposure to toxic content as*

$$\frac{d \log(s_{i,1}^t / s_{i,1}^n)}{d \log(\bar{q}^t / \bar{q}^n)} = \theta$$

(SA2) *the influence effect, θ , is constant across time and users.*

(SA3) *users engagement in equilibrium is stable over time $s_{i,0}^t = s_{i,1}^t$ and $s_{i,0}^n = s_{i,1}^n$*

(SA4) *assignment probabilities are orthogonal to user preferences conditional on user's observed behavior, $E[q_{i,1}^t(D_i) | w_i^t, s_{i,0}^t, D_i] = E[q_{i,1}^t(D_i) | s_{i,0}^t, D_i]$*

(SA5) *users view all the content assigned to them, $q_{i,\tau}^t = v_{i,\tau}^t$ and $q_{i,\tau}^n = v_{i,\tau}^n$, with $q_{i,\tau}^t + q_{i,\tau}^n = v_{i,\tau}^t + v_{i,\tau}^n = 1$*

Then, θ can be estimated using the following regression equation

$$E[\Delta B_{i,1} | D_i = 1] = \gamma_0 + \gamma_1 A_{i,0} \quad (23)$$

where, $\gamma_1 = -\theta$.

Proof. Consider Proposition 6 which gives

$$\log \left(\frac{s_{i,1}^t(1)}{s_{i,1}^n(1)} \right) - \log \left(\frac{s_{i,0}^t(1)}{s_{i,0}^n(1)} \right) = \theta \log \left(\frac{\bar{q}^t}{\bar{q}^n} \right) - \theta \log \left(\frac{v_{i,0}^t}{v_{i,0}^n} \right)$$

Then, consider the second order Taylor series expansion of $\log \left(\frac{v_{i,0}^t}{v_{i,0}^n} \right)$, around some fixed point $v_{i,0}^t = v_{i,0}^n = \kappa_1$, where κ_1 is some constant. Then,

$$\log \left(\frac{v_{i,0}^t}{v_{i,0}^n} \right) = \frac{1}{\kappa_1} A_{i,0}(1) + O(A_{i,0}(1))^2 \quad (24)$$

This gives the right-hand side of the required expression. Similarly, consider Taylor series

expansion of the following term around $\frac{s_{i,1}^t}{s_{i,1}^n} = \frac{s_{i,0}^t}{s_{i,0}^n}$

$$\begin{aligned} \log\left(\frac{s_{i,1}^t(1)}{s_{i,1}^n(1)}\right) - \log\left(\frac{s_{i,0}^t(1)}{s_{i,0}^n(1)}\right) &= \log\left(\frac{\frac{s_{i,1}^t(1)}{s_{i,1}^n(1)}}{\frac{s_{i,0}^t(1)}{s_{i,0}^n(1)}}\right) \\ &= \log\left(\frac{s_{i,1}^t(1)}{s_{i,1}^n(1)} - \frac{s_{i,0}^t(1)}{s_{i,0}^n(1)}\right) \\ &= \frac{1}{\kappa_1} \Delta B_{i,1}(1) \end{aligned}$$

which gives the required expression on the left-hand side, as the constant κ_1 cancels out from both sides of the relationship of interest, due to the constant term. \square

So, θ measures the behavioral effect of current exposure to toxic content as it gives the rate at which users update their behavior in line with lower exposure to toxic content. Intuitively, θ measures user preference for conformity with societal tastes, that are reflected on user feeds through q^t . Subsequently, θ is the influence parameter, measuring the effect of social norms relayed to a user through exposure to content feeds. This is true in the sample of treated users where, $-\gamma_1 = \theta$ is estimable. Then, $1 - \theta$ provides the appropriate elasticity of user behavior during intervention with respect to user behavior at *baseline*, or with respect to users' inherent tastes for such content.

This model provides the machinery to identify estimates of the stickiness or malleability in human behavior, in addition to the correct interpretation of these results. Furthermore, this interpretation is generalizable for users in both treatment and control groups. Therefore, the model arrives at a non-standard estimation strategy for an important parameter, that cannot be estimated on a social media platform that is typically in steady state. I exploit unique features of this setting and the structural model to estimate parameters that may not be estimated or correctly interpreted using a standard difference-in-difference approach.

C.3 Measurement Error

The estimation strategy above shows that θ , or the influence of exposure to toxic content, is measured using a sample of users in the treatment group, whose exposure to content was completely random. The difference in odds of sharing between the two time periods corrects the bias induced by the omitted variable: users' unobserved preference for *sharing* content. Still, features of the platform and design of the experiment may induce measurement error in the proportion of toxic content viewed. This is because of *sampling errors*, i.e. users view only a fraction of content in the ranked lists of content (in a set order), that the algorithm generates for them in each time period.

Among *treated users at baseline*, each toxic post *viewed* is assumed to be a Bernoulli trial with probability $q_{i,0}^t$. Similarly, each non-toxic post viewed is assumed to be a Bernoulli trial with probability $q_{i,0}^n$. In each session therefore, the total number of toxic posts viewed is subject to measurement error, on account of the sampling procedure itself. However, since the sampling distribution of toxic and non-toxic views is known, the estimates can be corrected for measurement error using IV approaches (Schennach, 2016).

Consider the following linear classical measurement error set up. Suppose, $v_{i,0}^{t*}(1)$ and $v_{i,0}^{n*}(1)$ denote the true proportions of toxic and non-toxic content viewed respectively, that are observed with measurement error in the data.

$$\begin{aligned} v_{i,0}^t(1) &= v_{i,0}^{t*}(1) + ev_{i,0}^t(1) \\ v_{i,0}^n(1) &= v_{i,0}^{n*}(1) + ev_{i,0}^n(1) \end{aligned}$$

where, $ev_{i,0}^t$ and $ev_{i,0}^n$ denote the measurement error in the proportion of toxic and non-toxic content viewed respectively. In general, assume that $Cov(v_{i,0}^{t*}(1), ev_{i,0}^t(1)) = 0$ and $Cov(v_{i,0}^{n*}(1), ev_{i,0}^n(1)) = 0$. The estimators constructed from the strategy above are therefore, likely to suffer from attenuation bias due to the unobserved measurement error on the right-hand side of the estimating equation. I construct an instrumental variable to address this issue.

Note that $v_{i,0}^t$ is the average of toxic posts viewed over all the posts viewed (of any type) by a user. Consider the proportion of toxic posts viewed out of half of the total posts viewed,

$$v_{i,0}^{\frac{t}{2(-)}}(1) = \frac{\sum_{j=1}^{J/2} t_{ij,0}(1)}{J/2}, \quad v_{i,0}^{\frac{t}{2(+)}}(1) = \frac{\sum_{j=1+J/2}^J t_{ij,0}(1)}{J/2}$$

where, $j \in \{1, \dots, J\}$ indexes each post viewed by user i , so that $t_{ij,0}$ is a binary variable indicating whether post j was toxic or not, and $J/2$ indexes the median post. The first expression averages over the first half of posts per user (arranged in a random order) and is henceforth referred to as *half1*. Similarly, $v_{i,0}^{\frac{t}{2(+)}}$ denotes the fraction of toxic posts out of the second half of the total posts viewed (for brevity, this variable is henceforth referred to as *half2*). However, assuming that the measurement errors pertaining to each half of the posts, per user, are uncorrelated to each other, this fraction computed over the first half of posts can be instrumented by this variable constructed using the second half of the posts. That is to say,

$$Cov(ev_{i,0}^{\frac{t}{2(-)}}(1), ev_{i,0}^{\frac{t}{2(+)}}(1)) = 0 \quad (\text{AME})$$

Under this exclusion restriction, the attenuation bias in a 2SLS estimate of γ_1 is reduced to zero.

Proposition 8. *Measurement error in average toxic views is corrected by instrumenting the fraction of toxic posts viewed in the first half of posts viewed (*half1*), with the fraction of toxic posts viewed in the second half of posts viewed (*half2*) by a user in a session.*

Proof. The measurement error in these variables constructed using half the viewed posts, is written as

$$\begin{aligned} v_{i,0}^{\frac{t}{2(-)}}(1) &= v_{i,0}^{\frac{t*}{2(-)}}(1) + ev_{i,0}^{\frac{t}{2(-)}}(1) \\ v_{i,0}^{\frac{t}{2(+)}}(1) &= v_{i,0}^{\frac{t*}{2(+)}}(1) + ev_{i,0}^{\frac{t}{2(+)}}(1) \end{aligned}$$

where, as before $Cov(v_{i,0}^{\frac{t*}{2(-)}}(1), ev_{i,0}^{\frac{t}{2(-)}}(1)) = 0$ and $Cov(v_{i,0}^{\frac{t*}{2(+)}}(1), ev_{i,0}^{\frac{t}{2(+)}}(1)) = 0$.

Note the first stage regression using $half2$ as the instrumental variable,

$$\begin{aligned} v_{i,0}^{\frac{t}{2(-)}}(1) &= \alpha_0 + \alpha_1 v_{i,0}^{\frac{t}{2(+)}}(1) + \mu_{i,0} \\ &= \alpha_0 + \alpha_1(v_{i,0}^{\frac{t_*}{2}}(+)) + ev_{i,0}^{\frac{t}{2(+)}}(1) + \mu_{i,0} \end{aligned}$$

where, $Cov(v_{i,0}^{\frac{t}{2(+)}}(1), \mu_{i,0}) = 0$. Then, any bias in the estimates from the IV specification, due to measurement error in fraction of toxic posts viewed would depend on

$$\begin{aligned} Cov(v_{i,0}^{\frac{t}{2(-)}}(1), v_{i,0}^{\frac{t}{2(+)}}(1)) &= Cov(v_{i,0}^{\frac{t_*}{2(-)}}(1) + ev_{i,0}^{\frac{t}{2(-)}}(1), v_{i,0}^{\frac{t_*}{2(+)}}(1) + ev_{i,0}^{\frac{t}{2(+)}}(1)) \\ &= Cov(v_{i,0}^{\frac{t_*}{2(-)}}(1), v_{i,0}^{\frac{t_*}{2(+)}}(1)) \end{aligned}$$

Therefore, the IV approach eliminates measurement error, due to the exclusion restriction stated in (AME). The same strategy is applied to all users with regards to non-toxic content as well. This shows that the IV estimation strategy only depends on the true distribution of the main explanatory variable. \square

The OLS estimates suggest that this strategy does not account for measurement error, indeed the OLS strategy produces estimates that are biased towards zero. The IV estimates of θ show that a significant portion of user behavior is determined by user tastes. This implies that user behavior is not malleable with respect to exposure to new information.

C.4 Validation of structural estimates

The structural estimates show that users largely follow their old behavioral patterns, and that behavior is barely malleable according to new exposure to toxic content. I validate my estimation procedure that measures the rate at which users update their sharing behavior upon being randomly exposed to more non-toxic content during the intervention period.⁴⁶ This model correctly estimates the updating-behavior only for treated users, because for these users, exposure to toxic content in the baseline period is related to the engagement with such content only through the channel of behavioral response.

In the case of control users, exposure in the baseline period is related to engagement with toxic content during the intervention period through two channels, **(1) Direct:** User behavior is correlated across time, and **(2) Algorithmic:** Feed-ranking algorithms that expose users to toxic content to maximize engagement using prior user behavior. Since both these channels are correlated in the steady state, by design of the algorithm, the said relationship cannot be estimated in the sample of control users.

θ estimated using the control sample would be biased upwards as the omitted variable $(v_{i,1}^t/v_{i,1}^n)$ is correlated with both the sharing behavior $(s_{i,1}^t/s_{i,1}^n)$ as well as the exposure at baseline $(v_{i,0}^t/v_{i,0}^n)$ in the main estimating equation (23). This is true if there were sufficient variation in equilibrium sharing behavior across the two time periods, as control users are always in steady state. This relationship is not estimable when the outcome is the difference in sharing behavior between the two time periods $(s_{i,1}^t/s_{i,1}^n - s_{i,0}^t/s_{i,0}^n)$, in order to account

⁴⁶This is true for toxic-type treated users.

for unobserved heterogeneity in tastes among users. The steady state condition implies that the ratio of shares at baseline and during the intervention period is equal.

Therefore, estimates that employ the control sample are expected to be distinct from the main estimates above. Table H.9 and Figure G.11c show that this is indeed the case. This validates the main estimation strategy because the estimates from the same exercises using the distinct samples of treated and control users yield very distinct results. Additionally, Figure G.11b shows that exposure to toxic content *during the intervention period* has a much smaller effect on the odds of sharing such content. This also validates the main result, because the intervention period exposure is very likely concentrated around the average user's exposure, and is expected to produce different estimates.

C.5 Calibration

After uncovering the measurement error corrected estimates of the influence parameter θ , the model is calibrated using the data to estimate the parameters. This is helpful in understanding the extent to which the model is able to capture the underlying mechanisms of user behavior, and also to analyze the counterfactual distributions of treatment effects, under different possible values of θ . The model decomposes the contribution of each of these channels in driving the treatment effect, and offers insight into the effectiveness of the intervention, had users been more or less malleable to the content they were exposed to (i.e. for different values of θ).

The sample of treated users generates an estimate of $\theta = 0.16$, after correcting for the measurement error. I match moments of the empirical distribution of various outcomes, with the distributions simulated by the model, where θ is set to 0.16. This enables calibration of four main parameters of the model: (1) β , the consumption value of viewing posts, (2) α , the disutility from viewing unshareable posts, (3) η , the cost of sharing an additional post, (4) δ , the utility weight on conformity with societal norms. I use the method of simulated moments to estimate these parameters, using the data $\{s_{i,1}^t, v_{i,1}^t, S_{i,1}, N_{i,1}\}$, which is the proportion of toxic posts shared and viewed respectively, as well as the number of posts shared and viewed, respectively. I compute the empirical mean of each of these outcomes, separately for users with above and below median exposure to toxic content at baseline.

$$E[X] = \frac{1}{n/2} \sum_{i=1}^n x_i$$

Then, the model is defined by the following functions using the equilibrium conditions, as shown in section A.

$$s^t(v^t, p^t, \theta) = (v^t)^\theta (p^t)^{1-\theta} \quad (25)$$

$$N(\delta, \theta, \alpha, \eta, \beta, v^t, p^t) = \frac{-\alpha\delta\theta \left(\log \frac{v^t}{p^t} \right)^2 + \beta(\alpha + \eta)}{2\alpha\eta} \quad (26)$$

$$S(\delta, \theta, \alpha, \eta, N, v^t, p^t) = \frac{\delta\theta(1 - \theta) \left[(\log p^t)^2 - 2 \log v^t \log p^t + (v^t)^2 \right] + \frac{N}{\eta}}{2(\alpha + \eta)} \quad (27)$$

where, v^t , the proportion of viewed posts that are toxic, is the empirical analog of q^t , the assignment probabilities. Then, the moments of these functions are computed over some distribution of v^t , given by some density function $f(v^t)$. The moment conditions for users with lower proclivity to toxic content is given as,

$$E_1[s^t] = \int_0^{m^t} (v^t)^\theta (p^t)^{1-\theta} \cdot f(v^t) dv^t \quad (28)$$

$$E_1[N] = \int_0^{m^t} N(\delta, \theta, \alpha, \eta, \beta, v^t, p^t) \cdot f(v^t) dv^t \quad (29)$$

$$E_1[S] = \int_0^{m^t} S(\delta, \theta, \alpha, \eta, N, v^t, p^t) \cdot f(v^t) dv^t \quad (30)$$

where, m^t denotes the median value of the proportion of toxic posts shared, v^t , at baseline. Similarly, I write the moment conditions for users with higher proclivity to toxic content as,

$$E[s^t] = \int_{m^t}^{\infty} (v^t)^\theta (p^t)^{1-\theta} \cdot f(v^t) dv^t \quad (31)$$

$$E[N] = \int_{m^t}^{\infty} N(\delta, \theta, \alpha, \eta, \beta, v^t, p^t) \cdot f(v^t) dv^t \quad (32)$$

$$E[S] = \int_{m^t}^{\infty} S(\delta, \theta, \alpha, \eta, N, v^t, p^t) \cdot f(v^t) dv^t \quad (33)$$

I use numerical integration methods to evaluate these integrals, assuming $v^t \sim EVT1$. Subsequently, the empirical moments are matched with the simulated moments. The objective is to minimize the distance between the empirical and simulated moments, using the six moment conditions, given by equations (28) to (31). I use the Nelder-Mead simplex method to estimate the parameters of the model, which converge to the following values in 800 iterations, in this case (Gao and Han, 2012).

D Contextual Details

This Appendix provides the contextual background that makes this study highly timely and relevant. The context of this study is India, which is the second-largest market for social media platforms. However, the implications of the study are global, as the problems of misinformation and hate speech are universal.

D.1 Social Media and Indian Politics

The harms of social media have garnered significant attention in the US, but are arguably more severe in India. This is because as more Indians get connected to the Internet, they are more likely to be exposed to misinformation in an already polarized society. As a result, social media has been linked to organized hate crimes against minorities in India (Mukherjee, 2020).

The 2015 mob lynching of Mohammad Akhlaq, a Muslim farm worker, just outside of the National Capital Region of Delhi, highlighted the role that platforms like WhatsApp play in

spreading misinformation and exacerbating hate (Arun, 2019). This unfortunate incident is by no means an isolated one, making it especially important to study the factors that drive online political divisions in India.

Social media platforms like WhatsApp, Facebook, and Twitter face an unprecedented challenge of moderating content in this massive market. Attempts at moderating social media in the US have met with loud criticism from both sides of the political spectrum (Kominers and Shapiro, 2024). This task is even more difficult in India because these are American companies operating in a vastly different context, where hate speech on social media propagates in very atypical ways. The enormity of this task was most recently highlighted by Meta's inability to control anti-Muslim disinformation campaigns, just ahead of the Indian election of 2024.⁴⁷

Context-driven content moderation is a difficult challenge, also because the production of hate in the Indian context is very often linked with institutions that enable these platforms to do businesses. In agreeing with the government, social media platforms may be biased against opposition parties and pressure groups. This was seen, for instance, when Twitter suspended various accounts linked with the Farmer's Movement during massive protests against the controversial farm bills passed by the Indian Parliament (Dash et al., 2022). Similarly, the Wall Street Journal has alleged that Facebook India's Public Policy Head selectively shielded offensive posts of leaders of the ruling Bharatiya Janata Party (BJP), which has been variously described as Prime Minister Modi's Hindu Nationalist Party⁴⁸.

D.2 SM: ‘Indian TikTok’

SM is one of the most popular platforms in the country, as users can create and share content in over a dozen regional languages. On this platform, users interact with content generated by other users, who are typically super-stars or influencers in a particular genre, on the platform. Super star content creators could be comedians, dancers, or singers, who are sometimes supported by the platform, to enhance engagement.⁴⁹ While the platform is home to organic content creators, various politicians, and Bollywood celebrities also sometimes interact with their follower base on this platform.⁵⁰

Content based social networks, such as SM, are centered around topics like Politics, Religion, and Good Morning messages.⁵¹ Religious posts (both relating to Islam and Hinduism) are by far the most popular genre on the platform. India’s young population seem to seek out

⁴⁷See <https://thewire.in/tech/meta-approved-ai-manipulated-political-ads-during-india-election-report>

⁴⁸WSJ has alleged that BJP leader, T. Raja Singh, has said in Facebook posts that Rohingya Muslim immigrants should be shot, called Muslims traitors and threatened to raze mosques to the ground. PM Modi’s BJP has, in many instances, encourages blatant calls for violence against the country’s largest religious majority, i.e. Muslims.

⁴⁹See, for instance, the Instagram profile of ‘India’s First Trending Transgender Model’, who rose to fame through her dance videos on SM: <https://www.instagram.com/khushi1216/?hl=en>.

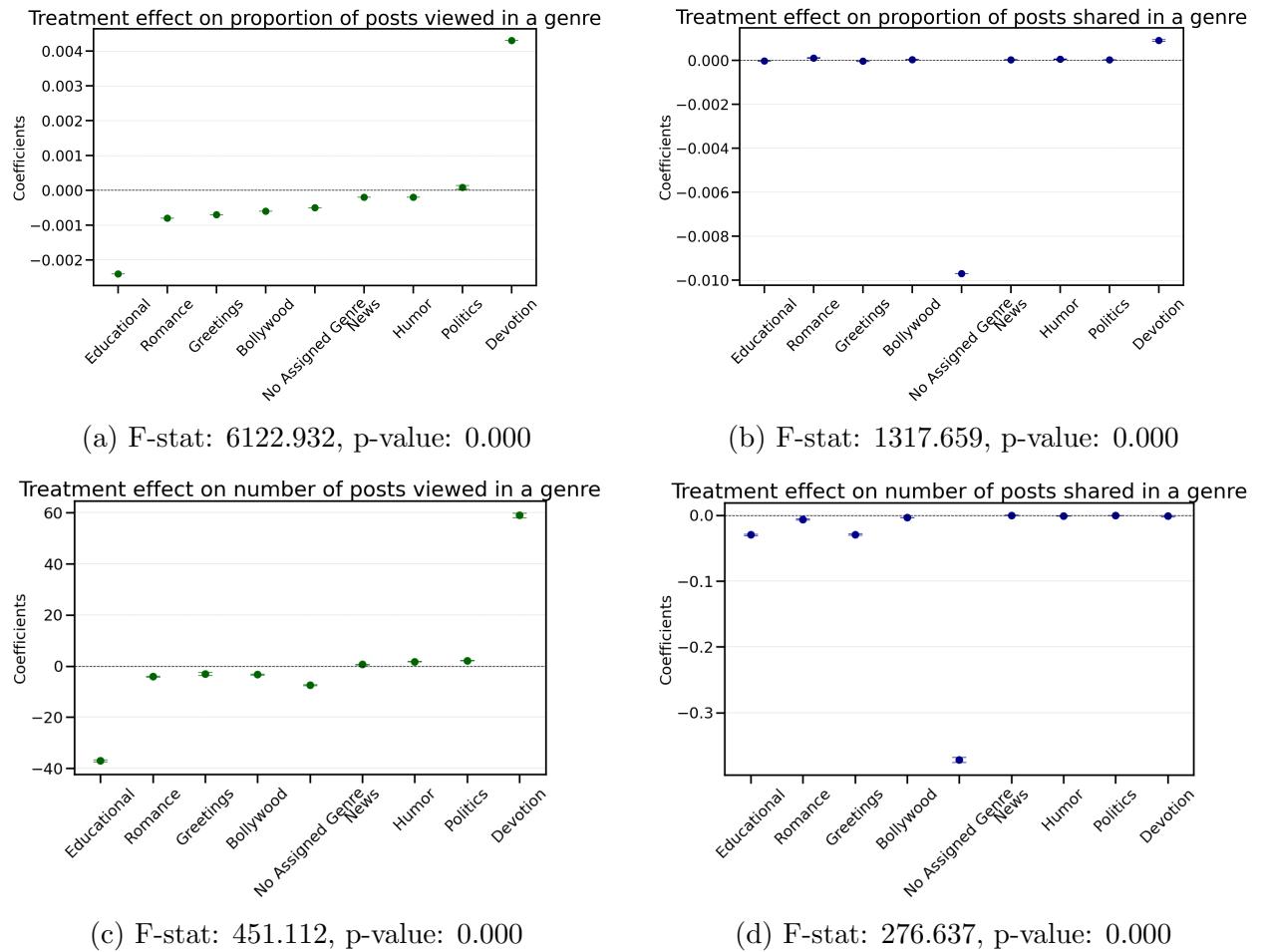
⁵⁰The source of this information is the author’s personal correspondence with the platform engineers and data scientists, via channels on Slack

⁵¹For context on the enormity of the ‘Good Morning!’ genre, see <https://www.wsj.com/articles/the-internet-is-filling-up-because-indians-are-sending-millions-of-good-morning-texts-1516640068>

relationship and dating advice, while older populations seem more invested in motivational content. Figure D.1 provides details on the treatment effects on the popularity of various genres on the platform.

Politics is the least favored genre on the platform, but 20% of the content in this genre was classified as toxic, during the first month of the intervention. I used the Perspective API to classify content as toxic or non-toxic, irrespective of the genre it belonged to. Posts are automatically classified into broad genres in the data, potentially using the user generated hash-tags associated with each post. The algorithms used to classify content were not disclosed by the platform to this author.

Figure D.1: Treatment effects on viewing and sharing content from various genres



Notes: These plots show that the treatment affected the number of posts shared and viewed in different genres. Although there was a large increase in exposure to devotional or religious content, the treatment effect on number and proportion of religious posts shared was much smaller. The treatment effect on views in educational, romance, bollywood, and greetings genres was negative. However, there was no commensurate decrease in the number of posts shared in these genres. Standard errors are robust at user level, and are computed at the 5% level of significance.

The interactions on SM are mostly conducted through the ‘trending’ feed, which is also the landing page when a user logs onto the platform (See Figure D.2). In this way, the

platform's interface resembles that of TikTok, than the more widely studied platforms like X (formerly, Twitter). User interaction in this network is possible only because of the similarity in content that users have shown to engage with. Therefore, SM is distinct from platforms like Facebook, where users engage with content from 'Friends' or from the 'Groups' they join.

Figure D.2: Landing page and trending tab on SM



Notes: This image shows the landing page and trending tab on the social media platform, SM. Users see a feed of image posts and the creator generated hashtags on the landing page, much like Instagram. Users can share, comment, like, or download the post to their phones. Sharing refers to sharing on WhatsApp, and not on the platform itself, for instance on user's own profile. This makes SM's interface very different from other platforms like X (formerly, Twitter), where users can share posts with their followers, through their profile on the platform. A user can see other users who liked and commented on a post, but not the users who shared the post. SM posts are classified into broad categories or genres like 'politics' (in this image), 'devotional,' 'romance,' 'Bollywood,' 'greetings,' and 'educational.'

E Embedding Model

Matrix Factorization algorithms provide some approximation of user preferences from their previous engagement with posts on the platform. This is done with the objective of optimizing user retention and engagement by serving them the type of content they have shown affinity towards in the past. The algorithm factorizes a matrix of engagement at the user-post level for some abstract set of user and post features.

E.1 Illustration: Control Algorithm

Consider an example with three users and two movies in Figure E.1. I use singular value decomposition (SVD) to factorize the engagement matrix into two-dimensional user and post

latent features. If we interpret dimension 1 of the factor matrices as movies relating to toxic genre, and dimension 2 as movies relating to comedy genre, then the factorization process generates a vector of weights for each user with respect to these attributes. In this example, the weights (or embeddings) reveal that users 1 and 3 have a higher proclivity for toxic movies, while user 2 is likely to rate comedy movies higher. As a result, these attribute weights enable a platform to serve toxic movies to users 1 and 3, and comedy movies to user 2, in order to maximize user satisfaction.

Figure E.1: An example of SVD decomposition into two-dimensional user embeddings U , eigenvalues Σ , and movie embeddings V^T

(a) Matrix representation of vector embeddings

$$R = \begin{pmatrix} 1 & 0 \\ 0 & 2 \\ 3 & 0 \end{pmatrix} = \begin{pmatrix} \frac{1}{\sqrt{10}} & 0 \\ 0 & 1 \\ \frac{3}{\sqrt{10}} & 0 \end{pmatrix} \cdot \begin{pmatrix} \sqrt{10} & 0 \\ 0 & 2 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

U Σ V^T

(b) Graphical representation of vector embeddings

Notes: In this example, a user-movie rating matrix is given by R , where three users rate two movies on a scale of 1 to 5. The idea is to learn user tastes in some low-dimensional space of latent features. This is because the dimensionality of the R matrix rises with the number of users and movies. Singular Value Decomposition (SVD) breaks this matrix down as (1) U represents the user embeddings (u_1 and u_2), showing how users relate to the abstract features; (2) Σ is a diagonal matrix containing singular values (σ_1 and σ_2), which scale the importance of each feature; (3) V^T represents the movie embeddings (v_1 and v_2), showing how movies relate to the abstract features. By multiplying U , Σ , and V^T back together, the original matrix R is reconstructed. The embeddings in U and V are plotted in a 2D space to visualize their relationships. These plots show that the first user is more interested in the first movie (or movies of that type), while the second user is more interested in the second movie (or movies of that type). The two dimensions represent abstract features that summarize the original data's structure and relationships. For example, dimension 1 could represent the toxic genre, while dimension 2 could represent the comedy genre. Then, the user embeddings would show how much each user likes toxic and comedy movies. In this example, the first user is more interested in toxic movies, while the second user is more interested in comedy movies.

More generally, this factorization process generates a vector of weights for each user with respect to some post attributes, so that a cross product of weights for user and post

latent features gives the predicted engagement matrix, or the scores that generate ranking of various posts for each user. These vector-weights in the space of some latent post/ user features are known as embeddings in the machine learning literature (Athey et al., 2021). The user features produced are latent representations of user behavior revealed in the past, and are produced by minimizing a known loss function using Stochastic Gradient Descent (Hastie et al., 2015). These latent features are represented as a multi-dimensional embedding vector, where each element in the vector represents the weight each user is predicted to put on some latent post attributes.⁵²

E.2 Illustration: Treatment Algorithm

In this experiment, the content recommendations for the control group are generated as per the usual personalization algorithm. For the treatment group, the algorithm is modified to randomly select user embeddings from the control group distribution. In the example below, user 2 is randomly chosen to be treated, and the embeddings for user 2 are replaced with the average of the embeddings for users 1 and 3.

Figure E.2: Matrix representation of vector embeddings, for treated and control users

$$\begin{pmatrix} \frac{1}{\sqrt{10}} & 0 \\ \cancel{\rho_{21}} & \cancel{\rho_{22}} \\ \frac{3}{\sqrt{10}} & 0 \end{pmatrix} \quad . \quad \begin{pmatrix} \sqrt{10} & 0 \\ 0 & 2 \end{pmatrix} \quad . \quad \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

U Σ V^T

Notes: This figure shows the user embeddings for the control group (in black) and the treatment group (in red). The treatment group embeddings, e.g. user 2, are generated by randomly selecting from the distribution of control group embeddings. This determines the order of different types of posts that are recommended to each user.

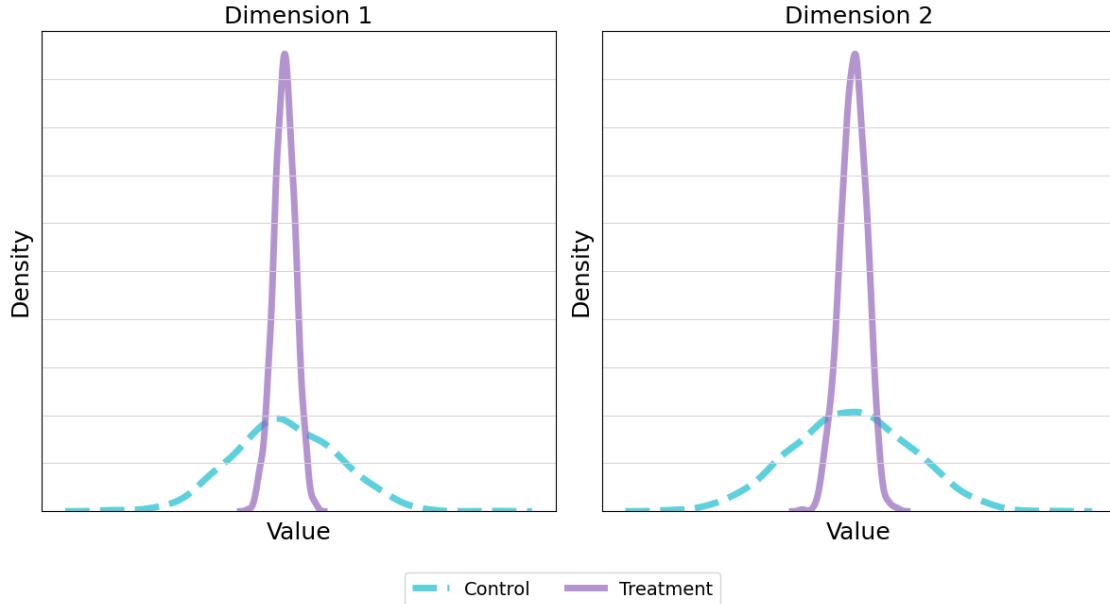
This example makes another subtle point. The embeddings generated for each treated user are equal to the average of the embeddings for the control group users. Therefore, there is not enough variation in the embedding assignment within the treatment group, as the treatment embeddings are concentrated around the mean embedding value, by application of the Central Limit Theorem (CLT). This is depicted in Figure E.3, for the simulated (two-dimensional) recommendation algorithm. This necessitates the need for a structural model to identify the effect of exposure on engagement.

Figure E.4 shows the distribution of a randomly selected set of user embeddings. As expected, the treatment group embeddings are more concentrated around the mean than the control group embeddings. Further, the CLT predicts that the treatment group embeddings follow a normal distribution, with a variance smaller than the control group embeddings. The dimensions of these embedding vectors could not be interpreted in any human-intelligible terms.⁵³

⁵²See (Ludwig and Mullainathan, 2024) for a recent and highly innovative use of contextual embeddings in a labor economics application.

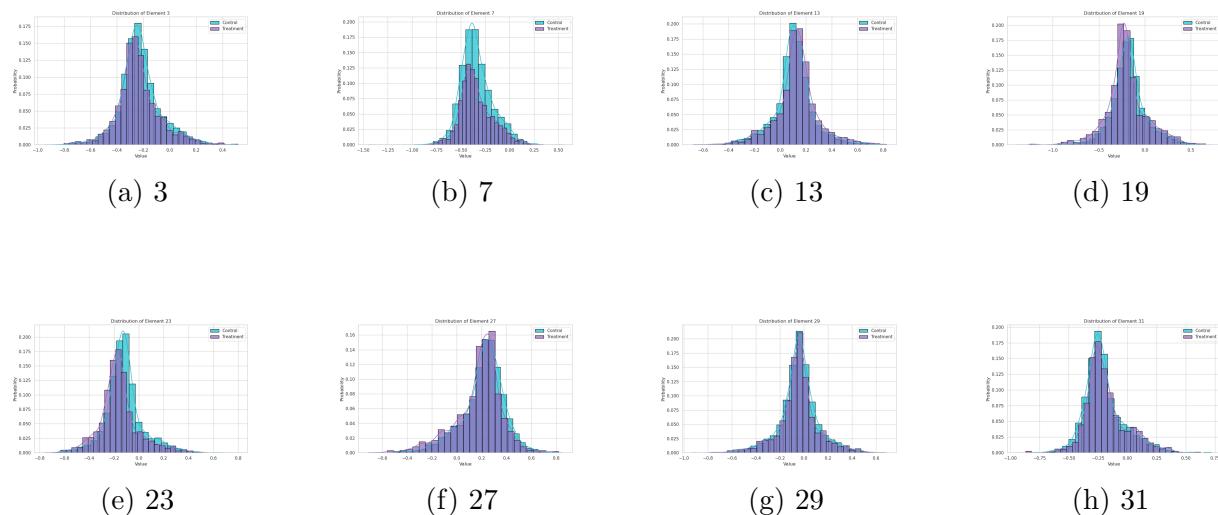
⁵³This was not for a lack of trying.

Figure E.3: Distribution of simulated two-dimensional embedding vectors



Notes: This graph shows that the two dimensions (components) of the embedding vector follow a Gaussian distribution, where the embeddings were simulated using a simple SVD algorithm and a matrix of engagement in the control group. An embedding is a representation of complex data in a lower-dimensional space. The dimensions of these vectors are abstract features that summarize the original data's structure and relationships. Then, the randomly selected embeddings for the treated users are centered around the mean of each embedding dimension, and the spread of control user embeddings is larger than the embeddings generated for treated users. This is because the treatment embeddings are drawn uniformly at random, each day, from a given sample of control embeddings during the intervention period (CLT).

Figure E.4: Treatment effect on embeddings across various Dimensions



Notes: This figure shows the empirical distributions of randomly selected dimensions of user embeddings in the treatment and control groups. On average, the user embeddings for the treatment group were more concentrated around the mean than the control group, as predicted by the simulated embeddings.

F Text Analysis

The post data is characterized by broad tag genres, employing user generated hashtags. The administrative data also consists of text on the images/ videos in the user generated posts, that was obtained through an automated optimal character reader (OCR). This is a rich source of information, and I adopt various methods to analyze the text data, in order to understand the qualitative nature, tone, and political slant of these posts.

F.1 Tokenization, Word Clouds, and Topic Models

I begin describing the text data by translating from the original Hindi, and summarizing the most common words in the political posts in Figure F.1. This summary measure is based on more than 20 million posts that were viewed and shared by users in the baseline and intervention periods. The text analysis currently excludes a dozen other Indian regional languages in which users can consumer or post content.

Figure F.1: Word clouds depicting words associated with highly toxic posts



Notes: This Figure shows word clouds constructed using the TF-IDF vectorizer, on posts classified into high and low toxicity categories respectively. Cut-off to classify posts into high and low toxicity categories is 0.2, based on the toxicity scores provided by Perspective API. The figure demonstrates overlap in words pertaining to religion in both categories, for example ‘Islam’ and the Hindu mythological god-king ‘Ram,’ who is also central to Hindu nation building agenda of the current ruling government. This highlights the need for contextual embeddings to characterize the text data. Perspective’s toxicity algorithm uses human labelled comments and BERT models to provide toxicity scores to each post, by representing posts in some latent space as embedding vectors.

Figure F.1 shows that the most common word in posts labelled as toxic is ‘Ram,’ which is a reference to legendary Hindu deity, who is said to have blessed the Hindu Nationalist project.⁵⁴ The Hindu nationalist project is a political ideology that is associated with the ruling party in India, that has been accused of promoting anti-minority sentiments, and even promoted outright calls for ethnic cleansing in extreme instances (Jaffrelot, 2021).

⁵⁴For instance, see Kalra (2021) for details on a coordinated campaign carried out in the name of Lord Ram, that was aimed at inciting violence against Muslims in different parts of India. This campaign, the *Ram Rath Yatra*, was a precursor to the 1992 Babri Masjid demolition. The temple built in place of this mosque was inaugurated by the current Prime Minister of India, Narendra Modi, in Junuary 2021. See <https://www.bbc.com/news/world-asia-india-68003095>

However, I find a significant overlap in the most common words across posts that were classified as toxic or not. For instance, the words ‘Ram,’ ‘Islam,’ ‘Allah’ are common in both toxic and non-toxic posts. This demonstrates that analyzing tokenized vector of words may lead to misleading conclusion. The text analysis must include sufficient information about the context in which the words are used. Therefore, I tried to gather a better sense of the context in which the words were used, by employing topic models on the text data (Handlan, 2020).

The LDA and BERT topic models provide useful information about the context in which the words are used, but the variation in topics, especially in the Politics genre, was too limited to be useful. Since, I am interested in the harm that posts can cause, I currently limit my analysis to hatefulness or toxicity of posts. This is a task best suited for some off-the-shelf classification algorithms, that I describe later. Therefore, I use semi-supervised Machine Learning methods that take contextual embeddings into account, while achieving a narrower objective: classifying posts as toxic or not.

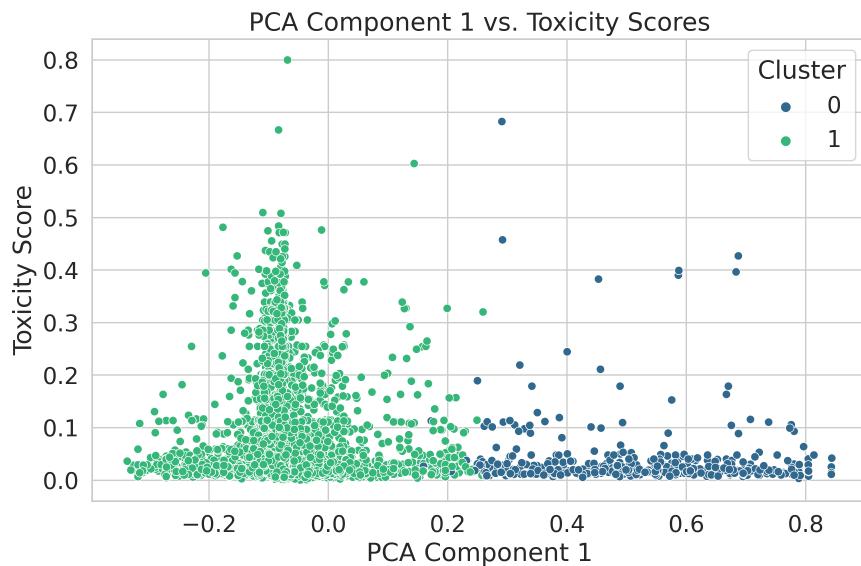
F.2 Toxicity Algorithm

In keeping with the literature on social media harms, I use the Perspective API to classify posts as toxic or not (Aridor et al., 2024). The Perspective API is a machine learning algorithm developed by Jigsaw at Google, that provides a machine learning solution to detect posts that are likely to harm a participant in a discussion. I provide examples to illustrate the toxicity classification algorithm in Table F.1.

Figure F.1 shows the most commonly occurring words (in English) across posts that were classified as toxic or not, and the overlap in words across the two groups. The overlap in words across the two groups also testifies that the toxicity scores are sensitive to contextual embeddings, that the Perspective algorithm extracts from the text data. This validates the need for contextual embeddings for text classification.

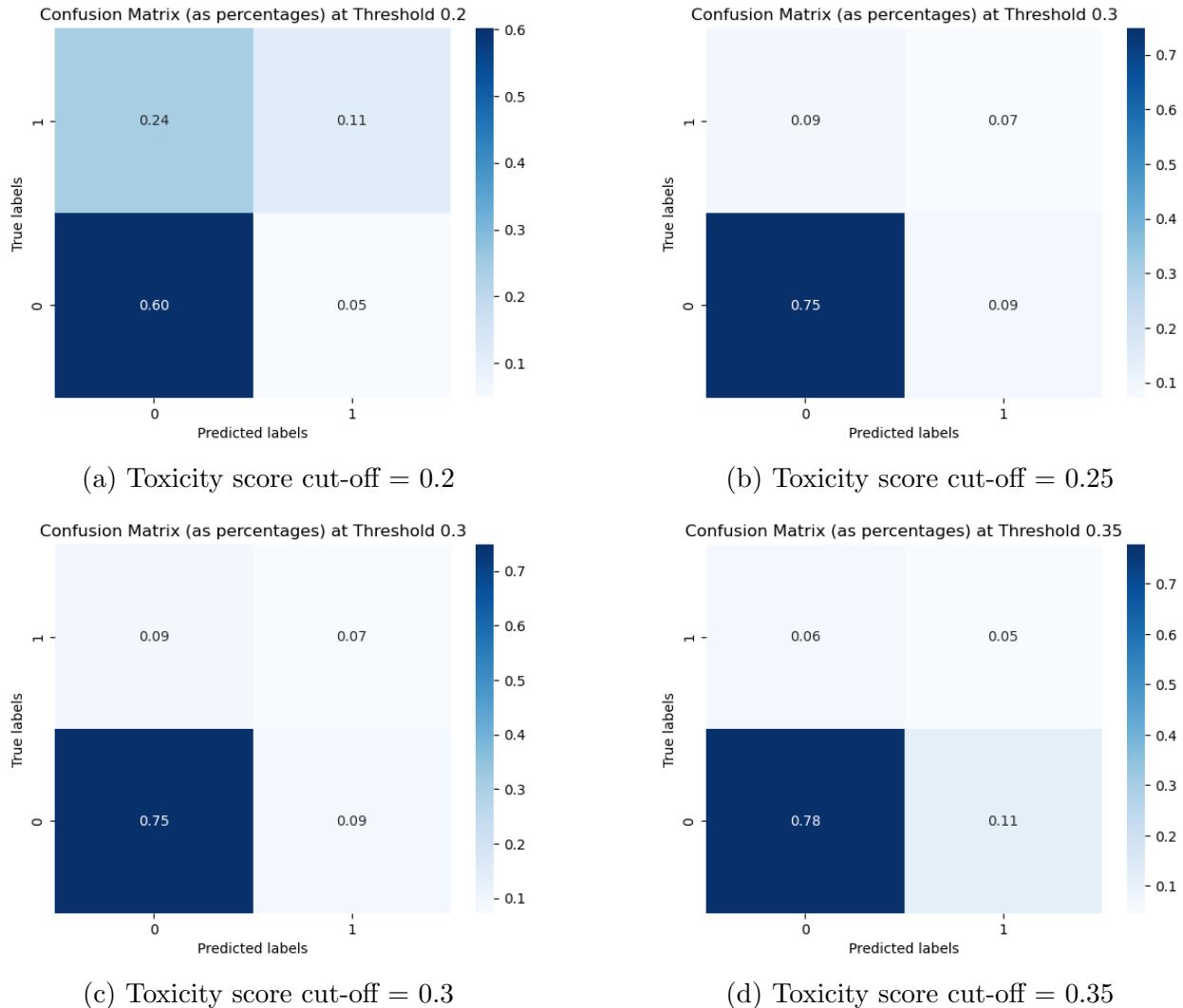
In Figure F.2, I plot and cluster the first principal component of the vectorized TF-IDF word representation for each document, against the corresponding toxicity scores for that post (Gentzkow et al., 2019; Ash and Hansen, 2023). I find that the separation between the word clusters corresponds to the 0.2 cut-off in the toxicity measure. I validate the performance of this method for multi-lingual abusive speech detection by comparing results with a choice of hate speech classification algorithms and with manually annotated posts that were viewed on SM for different toxicity thresholds. The confusion matrices in Figure F.3 show that the 0.2 cut-off has the best performance in terms of correctly classifying toxic posts. This criterion is important because toxicity is a rare outcome and can, therefore, make automatic detection difficult (Banerjee et al., 2023).

Figure F.2: Validating toxicity score threshold to construct binary outcome



Notes: The X-axis plots the first principal component of words in each document (post), obtained using PCA on the TF-IDF matrix of words. Y-axis corresponds to the toxicity score for the corresponding documents (posts), computed using the Perspective API. A k-means clustering algorithm is used to cluster the posts based on the first principal component. Toxicity scores for most posts in the first (blue) cluster of the first principal component rarely exceed 0.2. Therefore, 0.2 is chosen as the appropriate threshold for the binary outcome variable, indicating whether a post is toxic or not.

Figure F.3: Confusion matrices for different cut-offs in toxicity scores



Notes: These confusion matrices show Type I and Type II errors for four thresholds for classifying a post as toxic, namely 0.2, 0.25, 0.3, 0.35. User posts were assigned continuous toxicity scores using the Perspective API, and then classified as being toxic or not for the two thresholds. These scores were compared with posts annotated as hateful by two human annotators hired at Brown University. The threshold of 0.2 was chosen because toxic posts are correctly identified at this threshold with high accuracy. I argue that this is the most important criterion for the classification task, because toxic posts are a rare occurrence in the data.

Table F.1: Examples of text data (English translations) with toxicity scores

Text	Toxicity Score	Toxicity Classification
Break those rocks Jai Shri Ram which are standing in the path of religion and shoot those criminals who have dirty intentions on the women of our country	0.399	Toxic
LIVE LATEST UPDATES 0.01% population wants 'Khalistan.' 18% want 'Ghazwa-e-Hind' and 80% want cheap onions and tomatoes. It is bitter but true.	0.327	Toxic
People travelling on "Bharat Jodo" route are now facing problem with the name "Bharat" instead of India.	0.172	Non-Toxic
Mohammed Shamim's disgusting act ! Lakhs of pilgrims kept trusting Mohammed Shamim... Mohammed Shamim used to make tea from urine water and sell it. Mohammed Shamim used to run a shop in Kerala's Sabarimala temple premises.	0.479	Toxic
00 Death does not occur only when the soul leaves the body. He is also dead who remains silent even after seeing his religion and culture being attacked. 00	0.174	Non-Toxic
Giqa Bihar wire procession of thieves (temple thief) (coal thief) (fodder four) (land thief)	0.361	Toxic
Bhajanlal Sharma will be the new Chief Minister of Rajasthan.	0.008	Non-Toxic
Don't make us jokers, when Christians being 2% do not celebrate Ramnavami, why do we Hindus being 80% celebrate Christmas, joke our children on 25th December, Jai Satya Sanatan	0.361	Toxic
In this I.N.D.I.A alliance Everyone is against "Ram" and those who are not with Ram are of no use to us Jai Shri Ram	0.267	Toxic
Why has it been proved that sycophants are the biggest problem? Who is the master of sycophants? He is the biggest problem.	0.061	Non-Toxic

Notes: The table shows examples of text data in English, with toxicity scores provided by the Perspective API. The toxicity score is a continuous measure that ranges from 0 to 1, with 0 indicating healthy contributions and 1 indicating very toxic content. The Perspective API uses a mix of supervised and semi-supervised machine learning methods, and is sensitive to context while assigning toxicity scores. The Perspective API is widely used in academic research and by publishers to identify and filter out abusive comments.

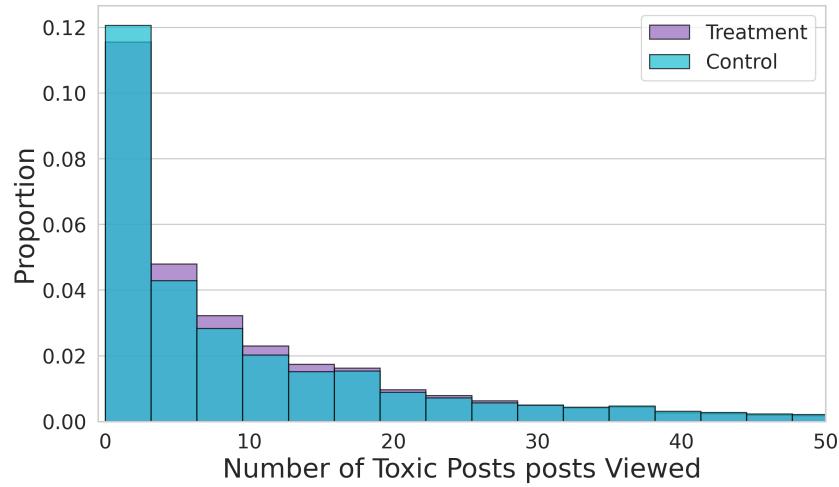
G Supplementary Figures

Figure G.1: Comparison of means across treatment and control, for key outcomes

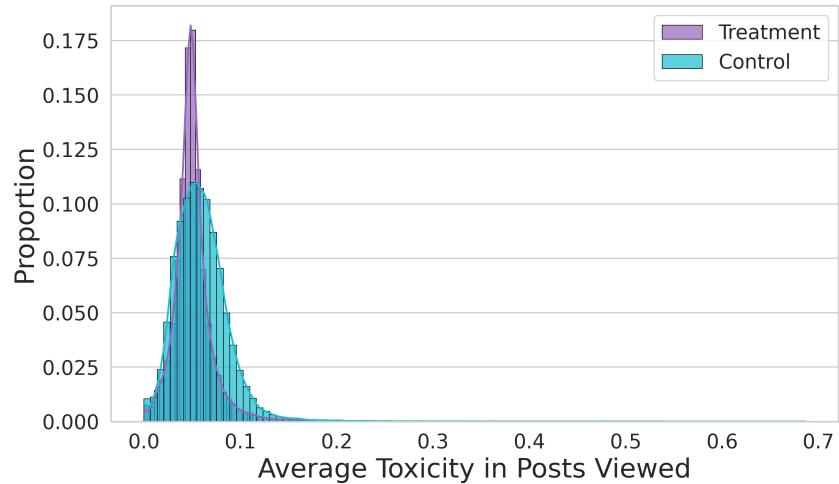


Notes: This Figure shows the trade-off between user engagement and the propagation of harmful content on social media. During the first month of the intervention, treated users were, on average, exposed to less toxic content, but were also less active on the platform. This highlights the costs (in terms of reduced user engagement with the platform), and benefits (in terms of reduced engagement with toxic content) of the intervention. Further, the decrease in toxic shares is not as large as the total decrease in shares, or the decrease in toxic views. User behavior is said to be inelastic with respect to toxic content because the ratio toxic shares to total shares is significantly higher in the treatment (3.16%), than in the control group (2.55%). Stickiness in sharing behavior with respect to toxic content is explained by the structural model, which quantifies the extent to which reduced toxic sharing is driven by the influence of reduced exposure to toxic content. Standard errors are depicted using confidence intervals around the means.

Figure G.2: Distribution of exposure to toxic content during intervention period



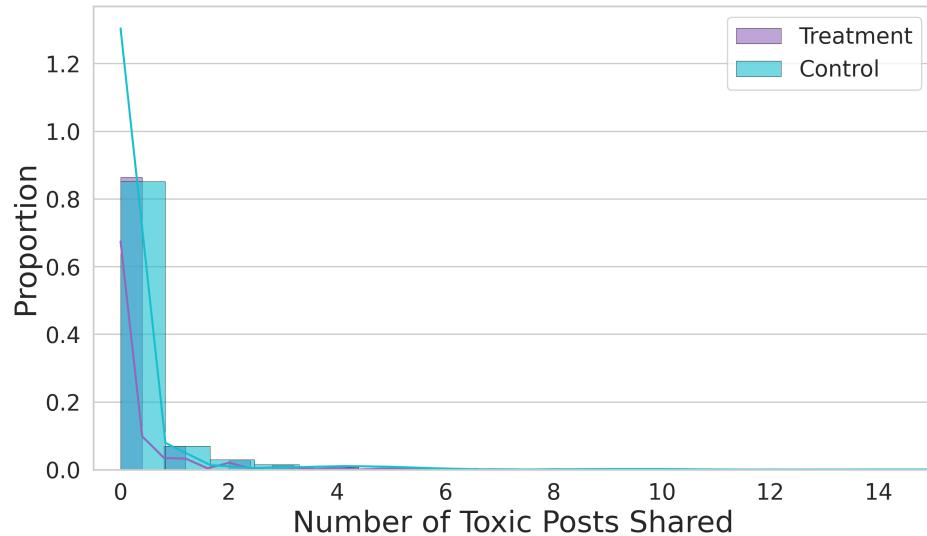
(a) Number of toxic posts viewed (with binary indicator for post toxicity)



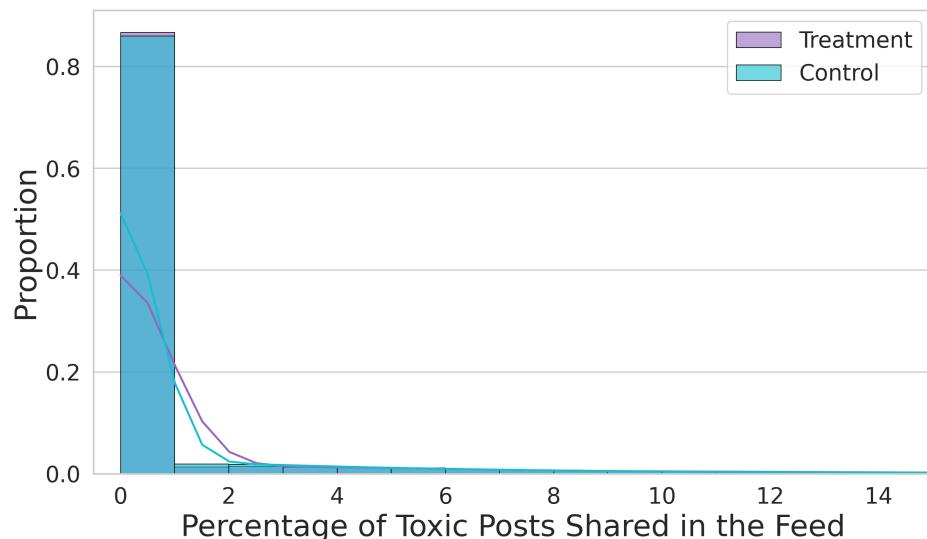
(b) Average toxicity scores on posts viewed (with continuous toxicity scores)

Notes: This Figure plots the raw data on the number of toxic posts viewed by users during the intervention period. The top panel uses the 0.2 threshold to classify a post as toxic, which generates a binary variable. The bottom panel uses the continuous toxicity score to measure the average toxicity of a user's feed. The distribution of toxic views for control users is to the left of the distribution for treated users. This is consistent with the main result that the intervention reduced exposure to toxic content for the average user in the treated user in the experimental sample.

Figure G.3: Distribution of engagement with toxic content during intervention period



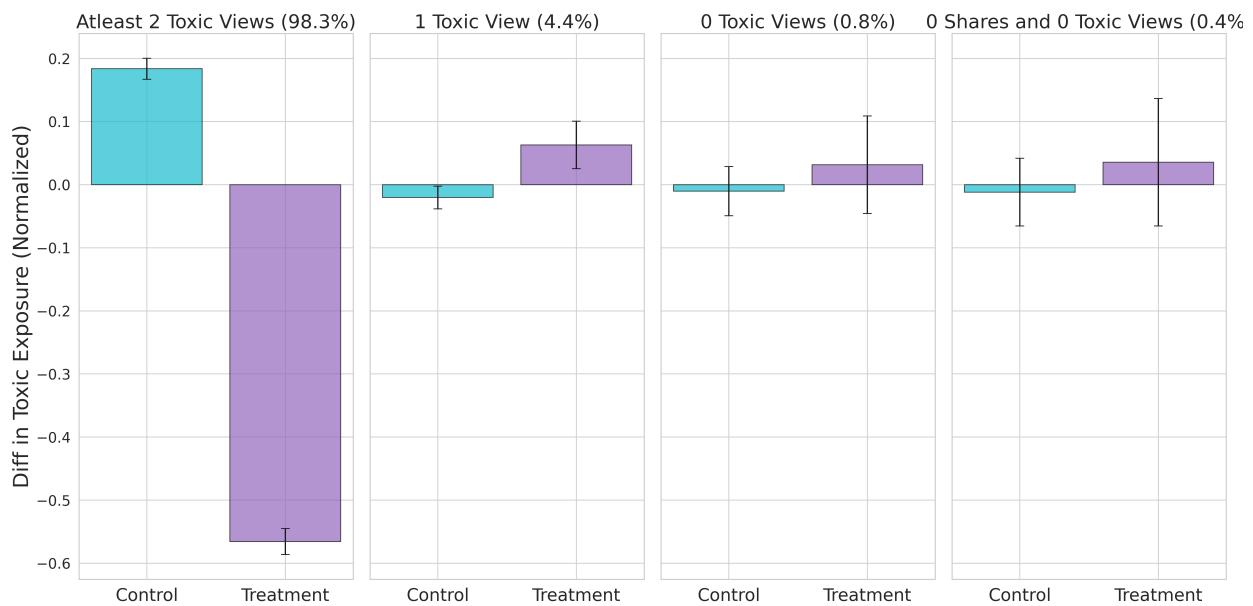
(a) Number of toxic posts shared



(b) Percentage of posts shared that are toxic

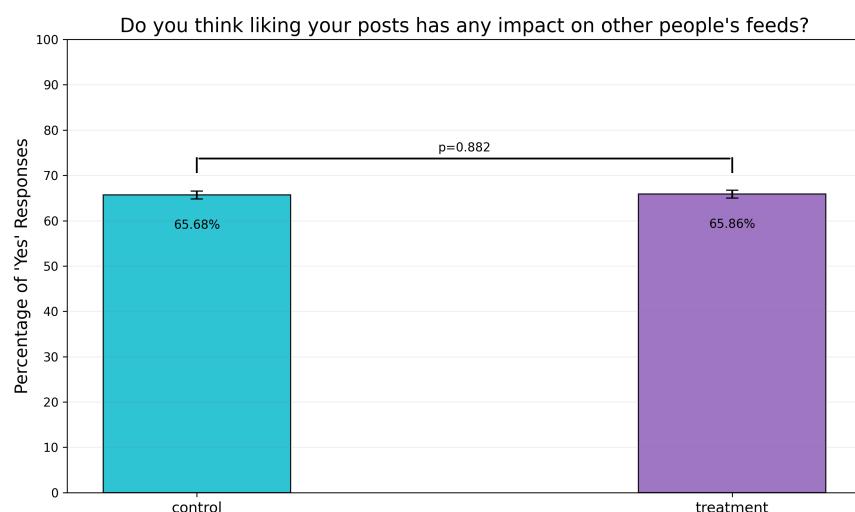
Notes: This Figure plots the raw data on toxic shares for treated and control users, and shows that the distribution toxic posts shared by control users first order stochastically dominates the distribution for treated users. Panel (a) provides the number of toxic posts shared, where a toxic share is defined as a shared post with toxicity score greater than 0.2. Panel (b) provides the percentage of shares that are toxic, where the proportion is defined as the number of toxic shares divided by the total number of shares.

Figure G.4: Difference between toxic views at intervention period and baseline, by user engagement at baseline



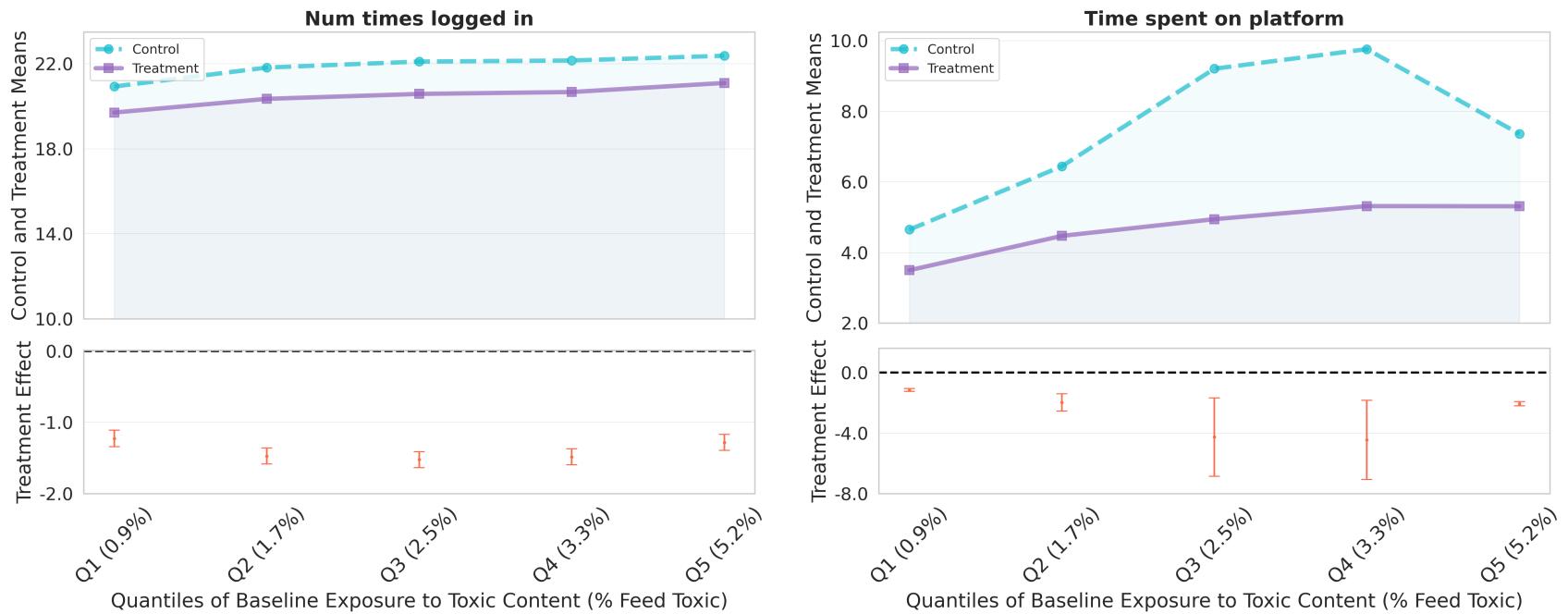
Notes: This Figure plots the raw data showing difference between toxic views during the intervention period and baseline, for users with different levels of toxic engagement at baseline. The averages have been normalized to have a mean of 0 and a standard deviation of 1. Percentage of users of a type (by engagement at baseline) in the experimental sample is given in parentheses. For example, 98.3% of users in the sample viewed at least two toxic posts at baseline. This Figure shows that these users saw fewer toxic posts during the intervention period. Users who saw exactly one toxic post at baseline, form about 4.4% of the experimental sample, and saw a larger number of toxic posts if they were treated.

Figure G.5: Salience of personalization algorithms



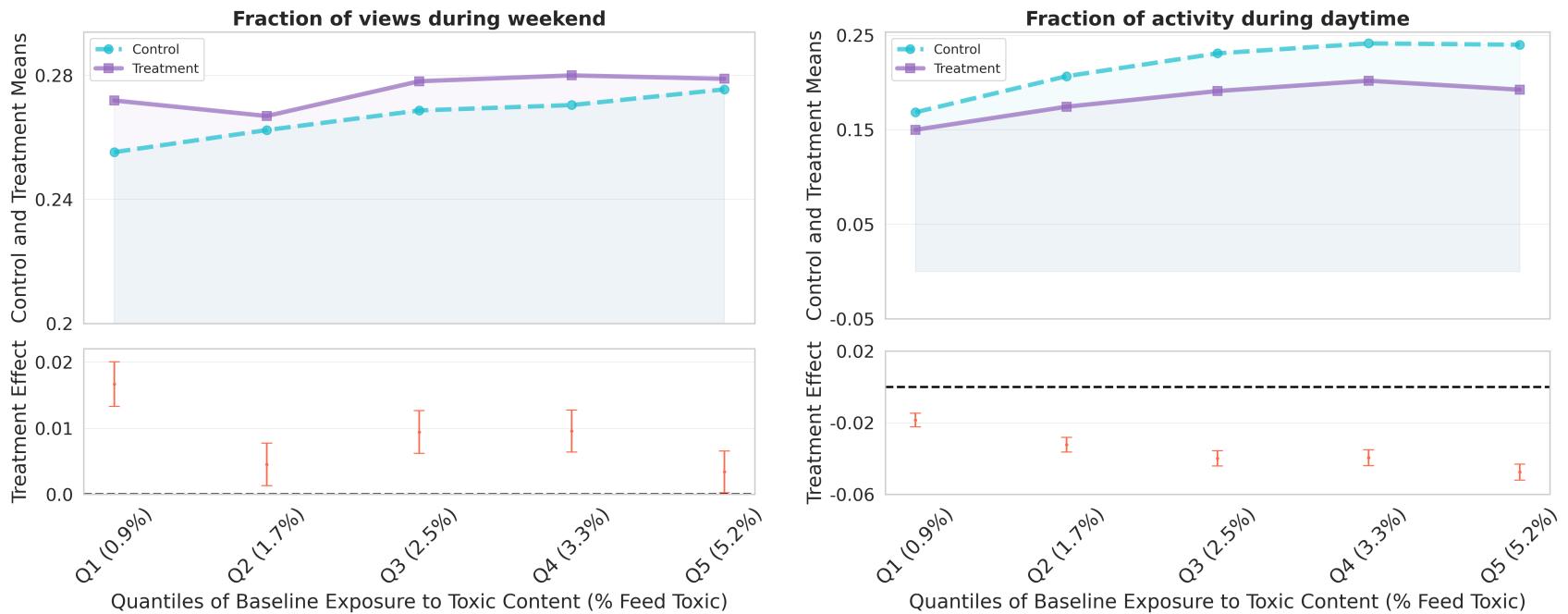
Notes: This Figure shows that the personalization algorithm is salient to users. A subset of users in the experimental sample were randomly selected for a follow-up survey ($N = 8,387$), and asked whether they thought their likes and shares changed the content in other users' feeds. More than 65% of the users said that they believed that their SM activity changes other people's feeds, and there were no differences in this response by treatment status. Uncertain responses were dropped before computing these percentages, and the error bars report standard errors of the means. The survey was conducted at the end of the intervention period, with 4,236 users randomly sampled from the treatment group, and the remaining 4,151 users sampled from the control group.

Figure G.6: Treatment effects on overall platform usage, by user type



Notes: This figure shows that the treatment reduced both the total time spent on the platform (in hours) and the number of times they logged on to the app. Further, there seems to be a significant reduction in the time spent for users in Q5 compared to Q1. The bottom panel in each figure shows the magnitude of treatment effects (coefficient plots), and the top panel shows the means of the outcome variable in each quantile of treatment and the control group. All regressions were run at the user level, and robust standard errors were computed.

Figure G.7: Treatment effects on auxiliary outcomes, by user type



Notes: This figure shows that the intervention changed the quality of user engagement on the platform.

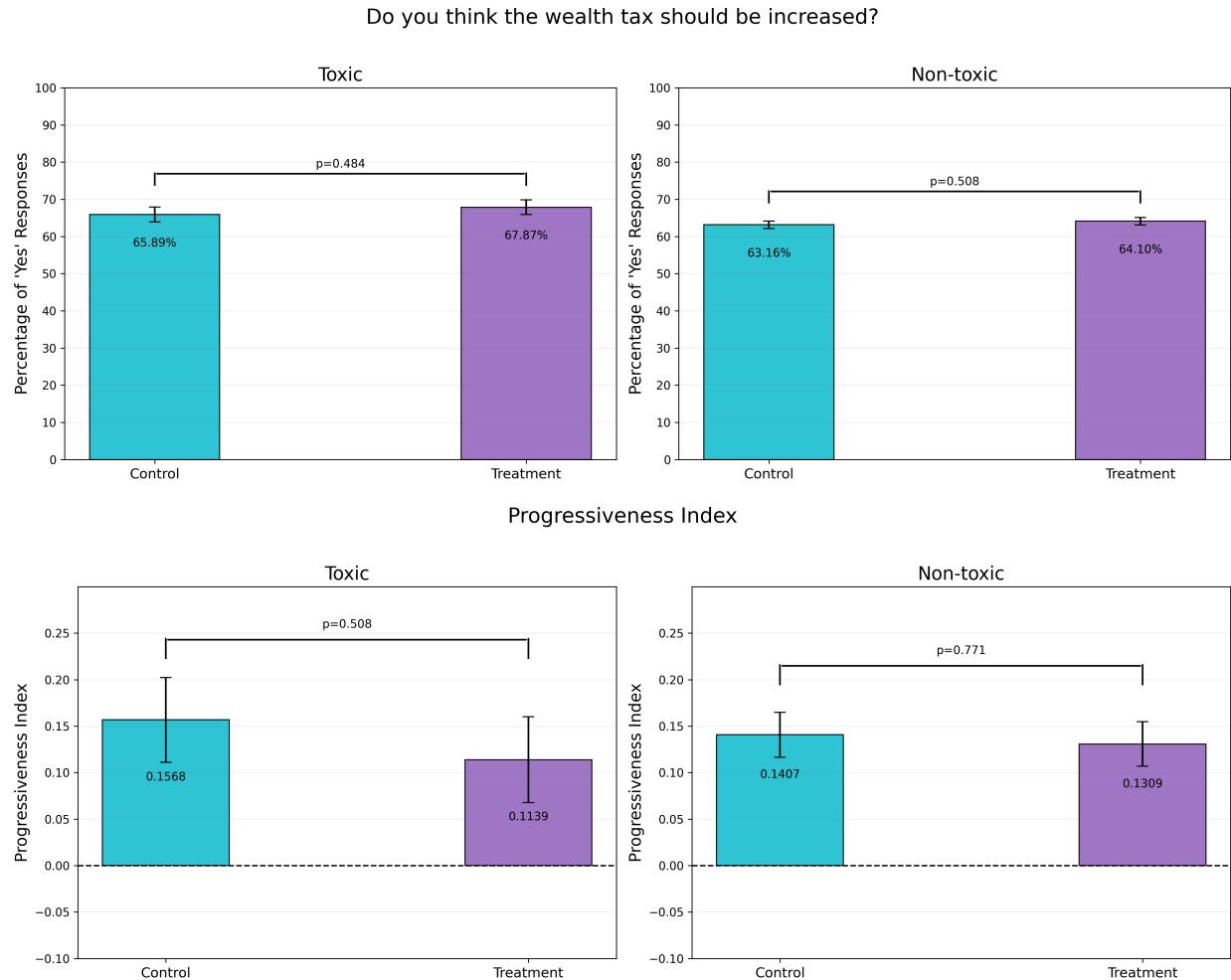
This is because treated users were more likely to use the platform during the weekend, or in the night.

Users spent less on the platform during their working hours. This has significant implications for the

labor-leisure trade off, and questions about digital addiction, that are explored in a companion paper.

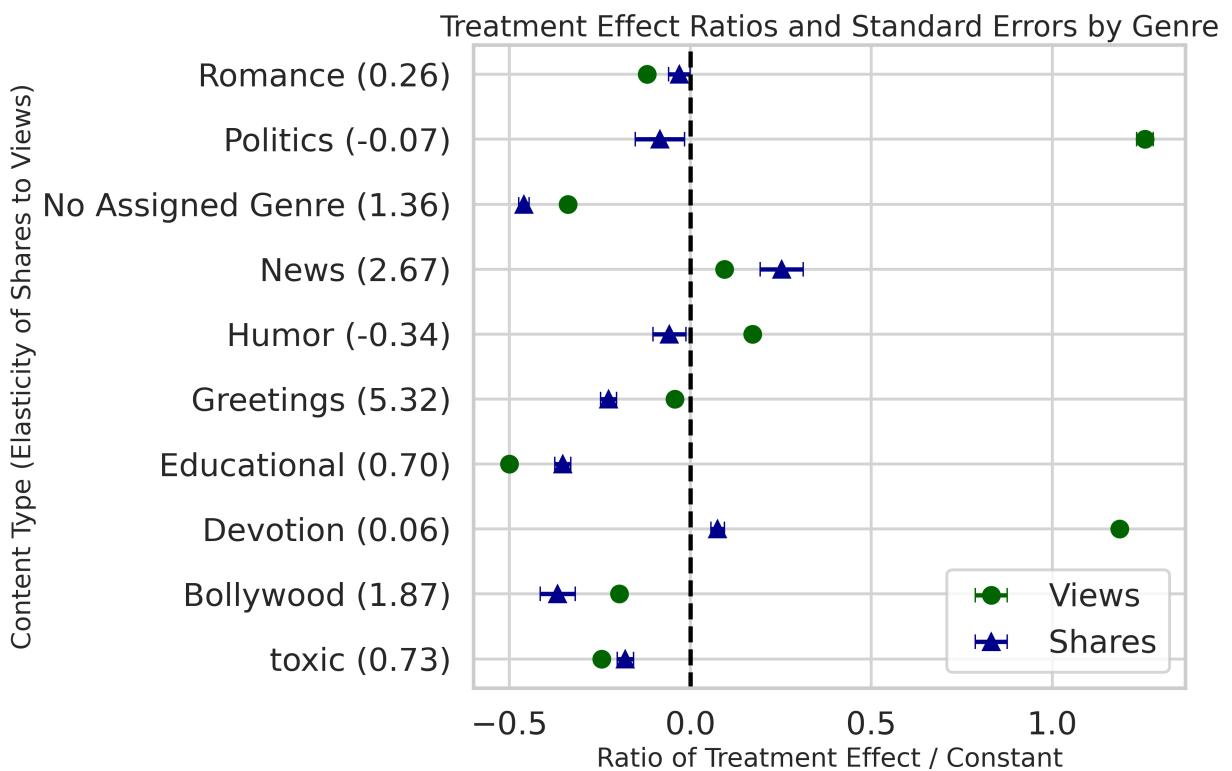
The bottom panel in each figure shows the magnitude of treatment effects (coefficient plots), and the top panel shows the means of the outcome variable in each quantile of treatment and the control group. All regressions were run at the user level, and robust standard errors were computed.

Figure G.8: Preferences over redistribution, by user type



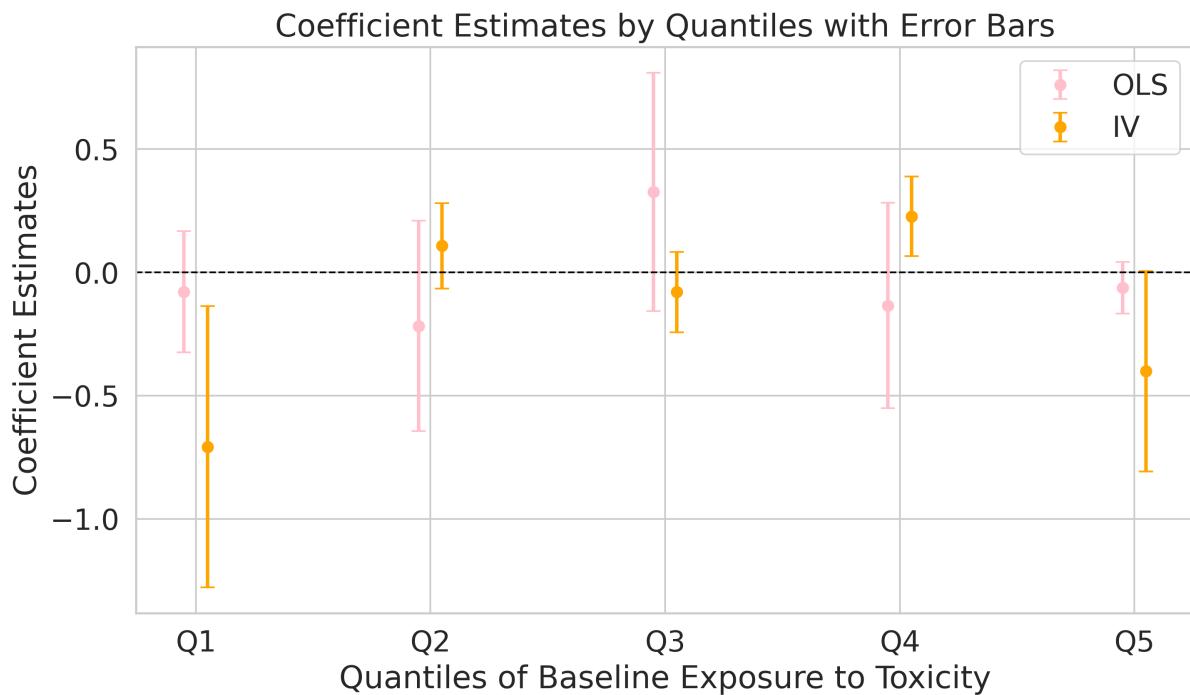
Notes: This Figure shows that the treatment did not affect users' preferences over redistribution, as reflected in the survey data ($N = 8,387$). This is consistent with the main results that the intervention led to very limited behavioral changes. Users in the random sample survey were asked if they thought that wealth should be redistributed, and the surveyor explained what a wealth tax would mean, in the telephonic surveys. Respondents could say 'Yes,' 'No,' or 'Don't know.' The uncertain responses were dropped before computing these percentages, standard errors, and p-values. Based on these responses, I also created a progressiveness index, from respondents' answers to different questions relating to affirmative action and wealth redistribution. Details of the survey instrument are contained in a companion paper. Respondents were further divided into toxic and non-toxic groups, based on their exposure to toxic content at baseline in the admin data. If a user's exposure to toxic content was above the median level at baseline, they were classified as a toxic user. Each group was balanced in terms of treatment status, on account of the random assignment and sample selection.

Figure G.9: Elasticity of sharing different types of content



Notes: This Figure shows the elasticity of sharing behavior with respect to exogenous content exposure due to treatment. Each marker shows the ratio of treatment effects to control means with respect to views and shares for different content types. Elasticities are computed by dividing the blue marker (triangle) with the green marker (circle). Relevant elasticities are shown in parentheses next to the labels for each content type. The plot highlights that while sharing behavior for toxic content is inelastic, user behavior for romantic, religious, and educational content is even more inelastic. Standard errors are robust and are computed at the 5% level of significance.

Figure G.10: Testing simplifying assumption in action-signalling model



Notes: This Figure shows that I cannot reject the hypothesis that heterogeneous users update their behavior, or are influenced by exposure, at equal rates. This justifies the use of a single parameter θ to capture the rate at which users update their behavior according to the perceived behavior of others, despite their underlying taste for such content. The plot was obtained by estimating the main structural equation from the model, in different sub-samples of users, based on their baseline toxic exposure. Later, I relax the assumption to estimate the model with malleable toxic users, and mechanical non-toxic users. All regressions were run at the user level, and robust standard errors were computed.

Figure G.11: Structural Estimates and Validation

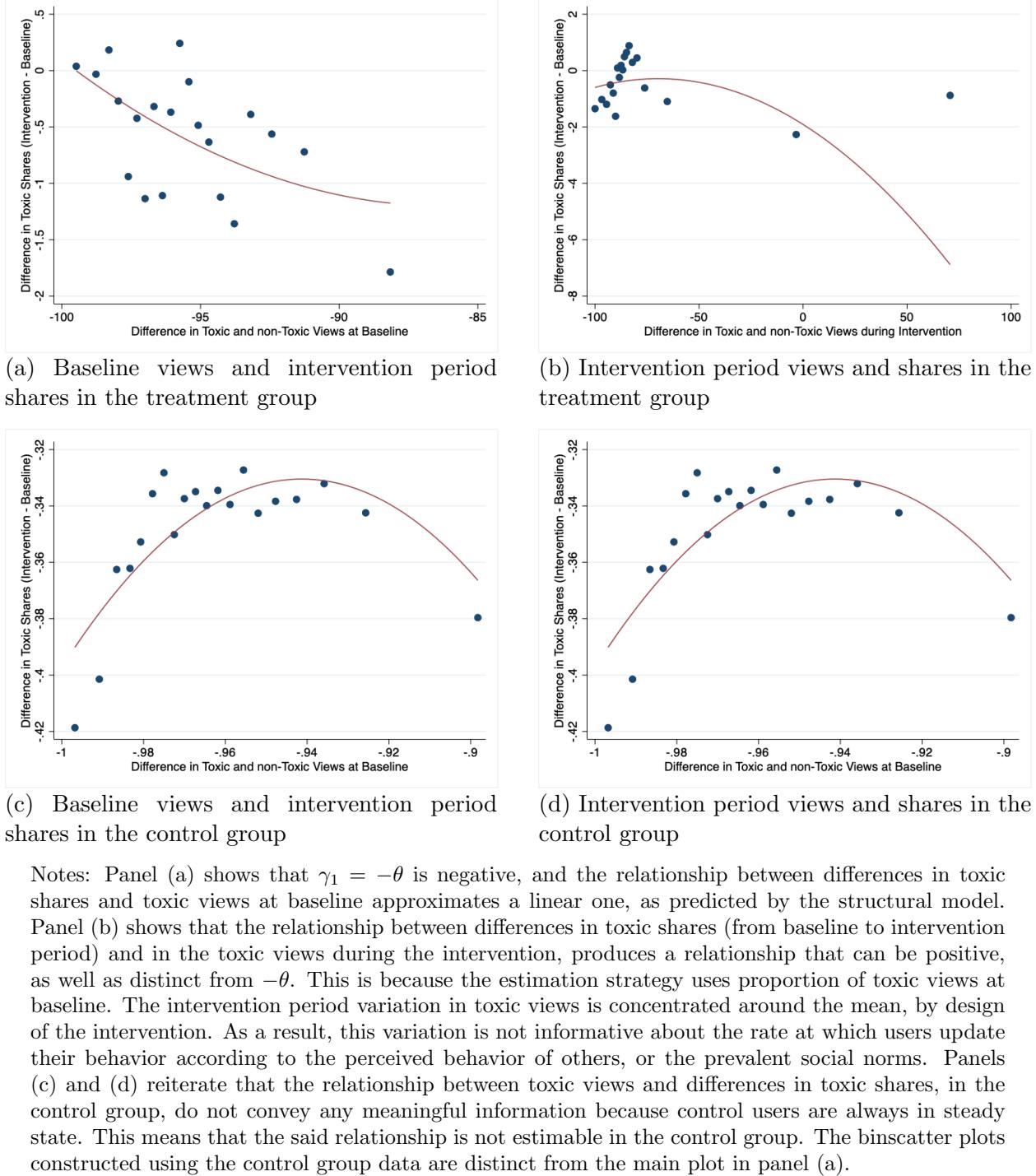
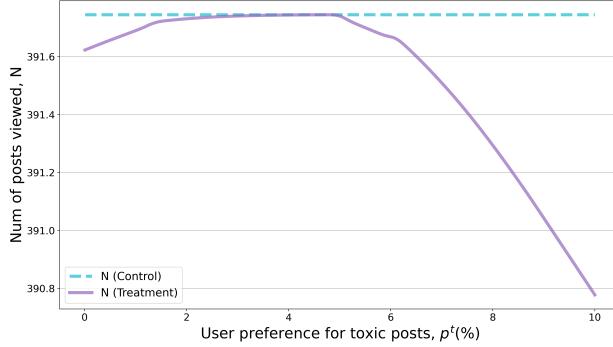
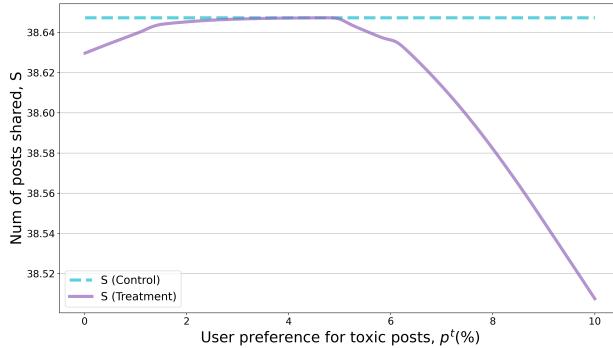


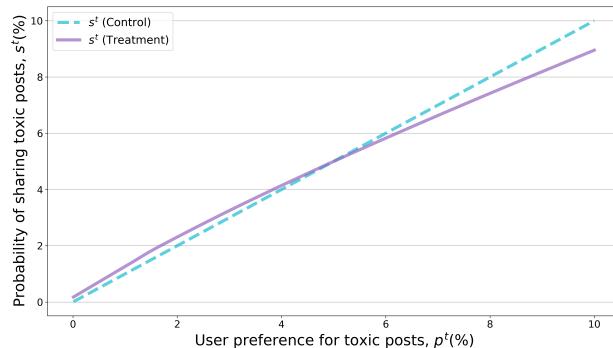
Figure G.12: Simulating key quantities in the model for heterogeneous influence factors (θ), by user type



(a) Number of posts viewed



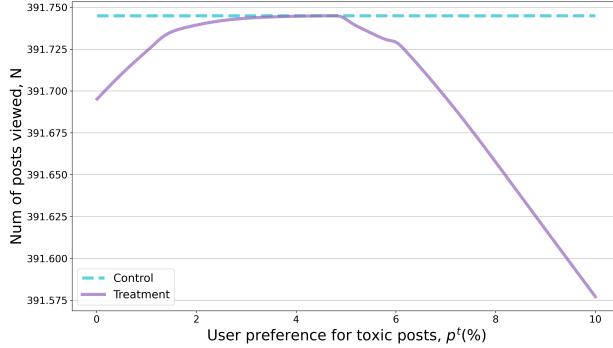
(b) Number of posts shared



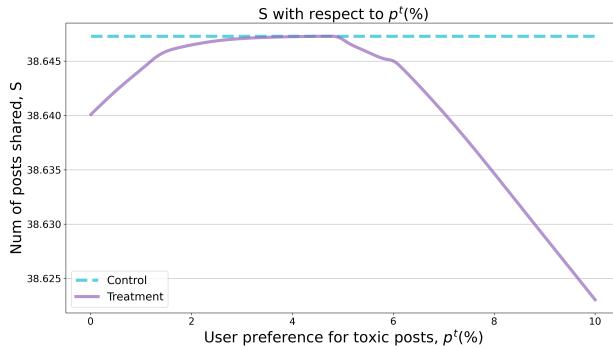
(c) Percentage of toxic posts shared

Notes: This figure shows that there is a larger decrease in engagement (number of posts viewed or shared) for toxic users, on the right extreme ends of the p^t distribution, when such users are assumed to be more malleable. The prediction differs from the main results in Figure 2 because of the assumption that $\theta = 0.01$ for non-toxic users, and $\theta = 0.16$ for toxic users. Then, total number of views and shares are decreasing in p^t , and the effects on overall engagement are not symmetric. This is still consistent with the effects on proportion of toxic shares being driven by users with low to medium proclivity for toxic content.

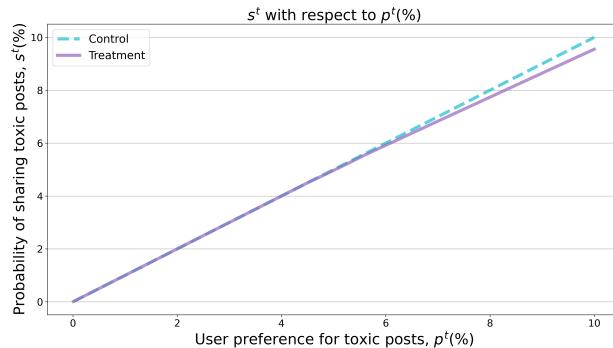
Figure G.13: Simulating policy counterfactuals for heterogeneous influence factors (θ), randomizing content feeds half the time



(a) Number of posts viewed



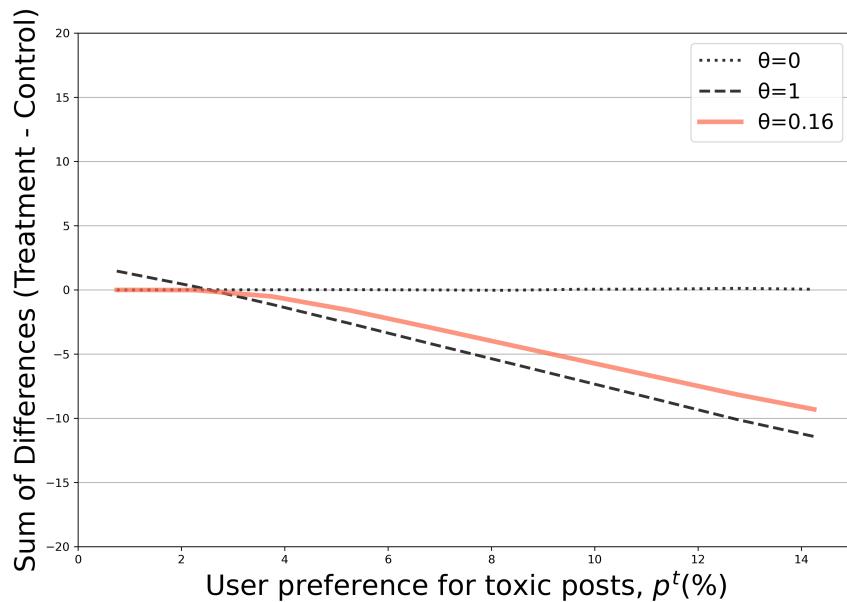
(b) Number of posts shared



(c) Percentage of toxic posts shared

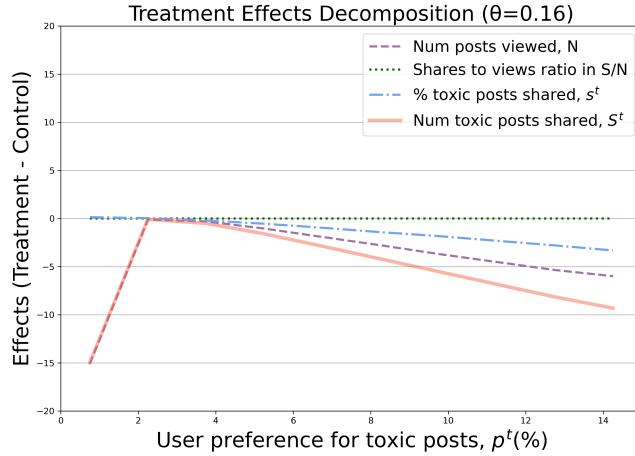
Notes: This figure simulates outcomes when the counterfactual policy randomizes half the content feed. As before, it shows that there is a larger decrease in engagement (number of posts viewed or shared) for toxic users, on the right extreme ends of the p^t distribution, when such users are assumed to be more malleable. Notably, users with lower proclivity to toxic content do not change their behavior, as the treatment effect on the probability of sharing toxic posts is zero. On the other hand, toxic users decrease both the number of posts viewed and shared, and the proportion of toxic posts shared.

Figure G.14: Treatment effects on total number of toxic posts shared for different influence factors, θ

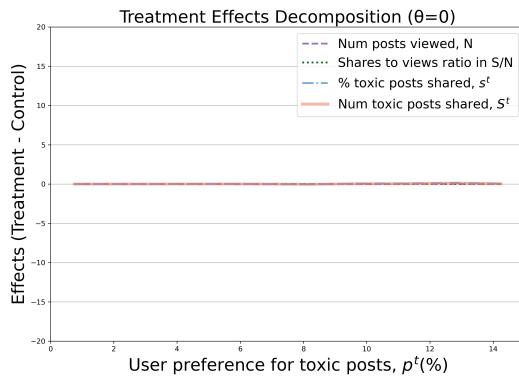


Notes: This figure shows that the simulated treatment effects on number of toxic posts shared is negative for more toxic users, when the rate at which exposure influences behavior is $\theta = 0.16$, as estimated using the structural model and the empirical distributions of various outcomes. This shows that, for the parameter values calibrated using the method of matching moments (See Appendix C.5 for details), the structural model correctly predicts that the treatment effect on the number of toxic posts shared is negative for toxic users. The treatment effect is then simulated for different influence regimes: $\theta = 0$, when users share content *mechanically*, and $\theta = 1$, when users are fully *malleable*. The treatment effect on the number of toxic posts shared is constant at zero, in the case of mechanical users (i.e. $\theta = 0$). However, when $\theta = 1$, users with lower proclivity to toxic content share more toxic content, because they are fully influenced by the content they are exposed to. Note that, the sharp decrease in the predicted treatment effect when $\theta = 0.16$ is driven by the model prediction that changes in overall engagement with the platform are symmetric across extreme users.

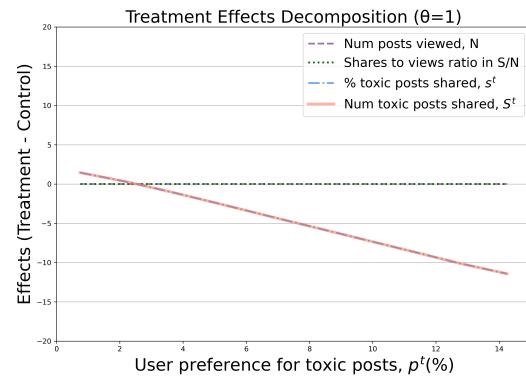
Figure G.15: Decomposition of treatment effects, in different updating regimes



(a) Estimated $\theta = 0.16$



(b) Mechanical users, $\theta = 0$



(c) Malleable users, $\theta = 1$

Notes: This Figure shows that if users were updating their behavior at the same rate θ , the decrease in the number of toxic posts shared is largely driven by the disengagement effect, especially for more toxic users (on the right extreme of the p^t distribution). It decomposes the treatment effect into its two constituent parts, namely, the engagement effect, on number of posts viewed N , as well as the shares to views ratio S/N , and the influence effect, on the probability of sharing toxic content s^t . Panel (a) shows that the reduction in total views (or the disengagement effect) has a higher contribution to the reduction in toxic shares, than the reduction in the probability of sharing toxic content. Panel (b) shows that there is no change in behavior if users were completely mechanical ($\theta = 0$). Panel (c) shows that treatment effect is entirely driven by the influence effect if users were completely malleable, and that the number of toxic posts would increase for non-toxic users if $\theta = 1$. The model generated simulated outcomes that are consistent with the data, on the right side of the p^t distribution. The behavior of non-toxic users is not predicted by the model with constant θ across users, and is consistent with the idea that non-toxic users are not as malleable.

H Supplementary Tables

Table H.1: Balance in treatment assignment across all observable characteristics

Variable	Control Mean	Difference (T - C)	Std.Err.
Observable User Characteristics			
State: gujarat	0.021	-0.019	0.014
State: uttar pradesh	0.105	-0.012	0.012
City: aligarh	0.002	0.019	0.027
City: bareilly	0.002	-0.010	0.024
City: dehradun	0.001	0.012	0.028
City: faizabad	0.002	-0.038	0.026
City: hardoi	0.002	-0.020	0.025
City: jaunpur	0.003	-0.028	0.022
City: khandwa	0.001	-0.007	0.037
City: latur	0.001	-0.068	0.033
City: north east delhi	0.001	-0.054	0.034
City: pratapgarh	0.002	0.031	0.024
City: raipur	0.004	-0.005	0.023
City: sitapur	0.002	-0.017	0.026
Gender: Male	0.699	-0.002	0.003
Age: 19-30	0.006	0.000	0.016
Week: 2016-28	0.000	-0.662	10.698
Week: 2022-38	0.012	-0.748	10.696
Baseline Behavior			
Num Posts Viewed	777.126	0.000	0.000
Num Posts Shared	22.045	-0.000	0.000
Num Logins	9.250	-0.000	0.000
Time Spent (in hours)	16.341	-0.000	0.000
Prop Activity during Daytime	0.097	-0.001	0.004
Prop Activity during Weekends	0.346	-0.007	0.005
Num Searched per Post Viewed	0.175	0.001	0.002
Prop Views in Humor Genre	0.051	-0.009	0.030
Prop Views in News Genre	0.058	-0.008	0.030
Prop Shares in Bollywood Genre	0.010	-0.037	0.012
Prop Shares in News Genre	0.009	-0.010	0.014
Prop of Views Toxic (%)	2.681	0.007	0.007
Prop of Shares Toxic (%)	2.241	-0.029	0.042
Tox Share to Tox View Ratio	1.023	-0.000	0.000
F-statistic:	0.984	p-value:	0.506
N			231814

Notes: This table shows balance in treatment assignment across all observable characteristics, using a single regression run at the user level. $D_i = \beta_0 + \sum_c \beta_c \mathbf{1}_i(\text{user characteristic} = c) + \varepsilon_i$, where D_i is binary variable taking value 1, when user i was assigned to the treatment group. The table shows a randomly selected set of coefficients. Weeks correspond to the date on which a user created her account. None of the observable characteristics are correlated with treatment assignment. I cannot reject null hypothesis of joint insignificance, with an F-statistic of 0.984 and p-value of 0.506. The regression was estimated at the user level. Robust standard errors in parentheses.

Table H.2: Regression results for all outcome variables

	Num Logins	Time Spent (in hours)	Num Posts Viewed
Treatment	-1.270** (0.042)	-2.531** (0.584)	-35.497** (2.208)
Mean Dep. Var. in Control	21.594** (0.021)	7.104** (0.583)	246.654** (1.361)
	Time Spent per Post	Num Posts Shared	Shares to Views Ratio
Treatment	-0.053** (0.002)	-6.367** (0.206)	-0.114** (0.007)
Mean Dep. Var. in Control	0.127** (0.001)	18.396** (0.131)	0.261** (0.004)
	Prop Activity on Weekends	Prop Activity during Daytime	Num Searches per Post Viewed
Treatment	0.010** (0.001)	-0.035** (0.002)	0.016** (0.001)
Mean Dep. Var. in Control	0.261** (0.001)	0.214** (0.001)	0.104** (0.001)
	Extreme Embedding Value	Num Toxic Posts Viewed	Perc Toxic Posts Viewed
Treatment	-0.005** (0.001)	-5.024** (0.172)	-0.641** (0.033)
Mean Dep. Var. in Control	0.030** (0.000)	18.806** (0.129)	7.416** (0.018)
	Num Toxic Posts Shared	Perc Toxic Posts Shared	Tox Share to Tox View Ratio
Treatment	-0.093** (0.010)	0.120** (0.038)	0.007** (0.001)
Mean Dep. Var. in Control	0.474** (0.006)	1.547** (0.018)	0.040** (0.001)
N		231814	

Notes: This table shows that the intervention caused disengagement with the platform, by showing negative and significant estimates of treatment effects on total number of posts viewed and shared, number of times users logged on, and total time spent. Each cell estimates the following regression equation with different outcomes (Y_i), $Y_i = \beta_0 + \beta_1 D_i + \varepsilon_i$. The average user viewed and shared fewer toxic posts, but the proportion of toxic posts shared increased. This table also shows that the intervention increased users' search costs of using the platform, as measured by the number of searches performed. This could explain why the treatment effect on proportion toxic shares is positive, despite the treatment effect on proportion toxic views being negative. Robust standard errors in parenthesis.
 $p < .0001^{***}$, $p < .01^{**}$, $p < .05^*$.

Table H.3: Balance in observable characteristics among stayers

Variable	Difference (T - C)	Standard Error
Observable User Characteristics		
State: gujarat	-0.023	0.017
City: auraiya	-0.038	0.047
City: bhiwani	-0.055	0.042
City: durg	-0.009	0.038
City: gwalior	-0.051	0.040
City: jalandhar	-0.024	0.045
City: kutch	0.009	0.045
City: mahendragarh	-0.010	0.050
City: mandsaur	-0.041	0.041
City: rajnandgaon	-0.047	0.043
City: ranga reddy	-0.010	0.039
City: ratlam	-0.035	0.041
City: sagar	-0.088	0.039
City: samastipur	-0.050	0.045
City: surat	-0.028	0.033
City: udaipur	0.045	0.043
City: udham singh nagar	-0.005	0.043
Gender: noneStated	-0.002	0.004
Age: 18-24	-0.000	0.005
Age: 45+	-0.016	0.012
N	159248	
F-stat: 0.942	p-value: 0.704	

Notes: This table shows that there were no systematic differences in observable characteristics among treated users who continued to use the platform during the intervention period. The table displays a randomly chosen subset of characteristics and corresponding coefficients from the estimating equation $D_i = \beta_0 + \sum_c \beta_c \mathbf{1}_i(\text{user characteristic} = c) + \varepsilon_i$, where D_i is binary variable taking value 1, when user i was assigned to the treatment group. This regression estimated the relationship between the characteristics on the right hand side, and treatment status on the left hand side, in the sample of stayers. None of the coefficients are individually or jointly significant when this regression was estimated using a sample of stayers, with an F-statistic of 0.942 and p-value of 0.704.

Table H.4: User characteristics correlated with the probability of leaving the platform

Probability of Leaving	β_c	$\beta_c \times D_i$
Treatment Effect	0.010 (0.011)	N/A N/A
Number of Views (Baseline)	-0.0000*** (0.0000)	0.0000 (0.0000)
Number of Shares (Baseline)	-0.0000 (0.0000)	0.0000 (0.0000)
Toxic Shares (Baseline)	0.0000 (0.0000)	-0.0000 (0.0001)
Toxic Views (Baseline)	-0.0001 (0.0004)	-0.0004 (0.0008)
Gender: Male	-0.0062*** (0.0011)	-0.0026 (0.0024)
Days since account created	0.0000*** (0.0000)	-0.0000 (0.0000)
User Age	0.0000 (0.0001)	0.0001 (0.0003)
Proportion content viewed on weekends	-0.0004 (0.0029)	0.0050 (0.0062)
Proportion content shared during daytime	-0.0010 (0.0013)	0.0028 (0.0028)
Share of views in Bollywood Genre	0.0094 (0.0053)	-0.0093 (0.0103)
Share of views in Devotion Genre	-0.0107* (0.0045)	-0.0001 (0.0092)
No Assigned Genre	0.0088 (0.0094)	0.0281 (0.0200)
Share of views in Greetings Genre	0.0044 (0.0046)	-0.0131 (0.0093)
Share of views in Humor Genre	0.0206** (0.0079)	0.0085 (0.0174)
Share of views in News Genre	0.0067 (0.0066)	-0.0178 (0.0137)
Share of views in Politics Genre	0.0150 (0.0405)	-0.0603 (0.0651)
Share of views in Romance Genre	0.0172** (0.0055)	0.0066 (0.0112)
N	231814	

Notes: This Table shows that, conditional on observable user characteristics, treatment assignment is not correlated with the probability of leaving the platform. This also shows that the treatment does not differentially impact the probability of leaving the platform, for given observable user characteristics. This means that the treated leavers are not systematically different from the control leavers. These results are obtained by estimating the regression equation $\mathbf{1}_i(\text{left platform} = \text{yes}) = \beta_0 + \beta_1 D_i + \sum_c \beta_c \mathbf{1}_i(\text{user characteristic} = c) + \sum_c \beta_{1c} D_i \mathbf{1}_i(\text{user characteristic} = c) + \varepsilon_i$, where $\mathbf{1}_i(\text{left platform} = \text{yes})$ is an indicator taking value 1, when user i leaves the platform. Column (1) reports estimated β_c 's, while column (2) reports estimated β_{1c} 's. Standard errors are robust at user level. $p < .0001^{***}$, $p < .01^{**}$, $p < .05^*$.

Table H.5: User characteristics correlated with the probability being exposed to more toxic content at baseline

Variable	β_c	$\beta_c \times D_i$
Treatment Effect	0.032 (0.032)	N/A N/A
Number of Views (Baseline)	-0.0000*** (0.0000)	0.0000 (0.0000)
Number of Shares (Baseline)	-0.0000 (0.0000)	0.0000 (0.0000)
Toxic Shares (Baseline)	0.0002 (0.0002)	-0.0001 (0.0003)
User Gender	-0.0158*** (0.0035)	-0.0099 (0.0074)
Days since account created	0.0000*** (0.0000)	-0.0000 (0.0000)
User Age	-0.0002 (0.0003)	-0.0000 (0.0007)
Proportion content viewed on weekends	-0.0133 (0.0085)	0.0202 (0.0187)
Proportion content shared during daytime	0.0025 (0.0041)	0.0049 (0.0090)
Share of views in Bollywood Genre	-0.0617*** (0.0137)	-0.0169 (0.0278)
Share of views in Devotion Genre	-0.0821*** (0.0131)	0.0024 (0.0266)
No Assigned Genre	-0.0308 (0.0261)	0.0398 (0.0516)
Share of views in Greetings Genre	-0.1031*** (0.0126)	-0.0521* (0.0252)
Share of views in Humor Genre	0.2879*** (0.0408)	0.1203 (0.1051)
Share of views in News Genre	0.1262*** (0.0278)	-0.0591 (0.0585)
Share of views in Politics Genre	0.0640 (0.1455)	-0.1950 (0.2219)
Share of views in Romance Genre	0.0042 (0.0169)	0.0246 (0.0341)
N	231814	

Notes: This Table shows the observable characteristics correlated with the probability of being exposed to more toxic content at baseline, irrespective of treatment assignment. This also reiterates that treatment assignment was balanced in baseline exposure to toxic content. These results are obtained by estimating the regression equation $propToxView_{baseline} = \beta_0 + \beta_1 D_i + \sum_c \beta_c \mathbf{1}_i (\text{user characteristic } = c) + \sum_c \beta_{1c} D_i \mathbf{1}_i (\text{user characteristic } = c) + \varepsilon_i$. Column (1) reports estimated β_c 's, while column (2) reports estimated β_{1c} 's. Standard errors are robust at user level are in parentheses. $p < .0001^{***}$, $p < .01^{**}$, $p < .05^*$.

Table H.6: Testing simplifying assumptions on sharing behavior

	(1)	(2)
	Total Toxic Posts Shared	Total non-Toxic Posts Shared
Total Toxic Posts Viewed	0.012*** (0.001)	
Total non-Toxic Posts Viewed		0.011*** (0.001)
Mean Dep. Var. in control group	1209.2*** (47.54)	34.30*** (1.465)
<i>N</i>	63041	63041

Notes: This Table provides evidence that the consumption value from sharing both toxic and non-toxic content is equal, which allows the simplifying assumption that each user has the same θ with respect to toxic and non-toxic content. The coefficient estimates are obtained from stacking regressions of (non-)toxic shares on (non-)toxic views. The statistical test of equality of coefficients could not reject the hypothesis that the coefficients from the two regressions are equal. Robust standard errors are in parentheses. $p < .0001^{***}$, $p < .01^{**}$, $p < .05^*$

Table H.7: Testing identifying assumption in structural model using control sample

	(1)	(2)	(3)
	Probability of sharing toxic post during intervention period		
Proportion of toxic posts shared at baseline	0.112*** (0.012)		0.820*** (0.091)
Proportion of toxic posts among first half of posts shared at baseline		0.290*** (0.057)	
<i>N</i>	52663	52663	52663

Notes: This Table tests the identifying assumption, derived from the steady state condition $s_{i,0}^t = s_{i,1}^t$. That is, all else equal, the probability of sharing toxic content for each user is expected to be equal in each time period. Column (3) shows that the measurement error corrected estimates of the slope coefficient is close to 1. The sample includes control users who shared at least one post at baseline. Robust standard errors in parenthesis. $p < .0001^{***}$, $p < .01^{**}$, $p < .05^*$

Table H.8: Structural estimates using OLS regressions with treated sample

Difference in shares (Current - Baseline)	
Difference in views at Baseline	-0.085* (0.039)
Constant	-8.486* (3.745)
N	63041

Notes: This table shows that the structural estimates of θ obtained using an OLS regressions are biased downwards. Dependent variable is differences in differences between probability of sharing toxic and non-toxic content, between intervention period and baseline, for treated users only. The explanatory variables are constructed by averaging differences between proportion of toxic and non-toxic posts viewed by treated users. Robust standard errors in parentheses. $p < 0.05^*$, $p < 0.01^{**}$, $p < 0.001^{***}$.

Table H.9: Validating structural estimates using OLS regression with control sample

	(1)	(2)
Difference in shares (Current - Baseline)		
Difference in views at baseline	0.312** (0.046)	
Difference in views		-0.060** (0.004)
Constant	-3.953 (4.414)	-38.561** (0.355)
N	168773	168773

Notes: Dependent variable is differences in differences between probability of sharing toxic and non-toxic content, between intervention period and baseline, for control users. The explanatory variables are constructed by averaging differences between proportion of toxic and non-toxic posts viewed by control users. θ estimated in the control sample, in Column (1), is biased upwards. Robust standard errors in parentheses. $p < 0.05^*$, $p < 0.01^{**}$, $p < 0.001^{***}$.

Table H.10: Estimation strategy for different model parameters

Parameter	Description	Source
θ	Rate of influence of exposure	OLS/ IV estimation
β	Consumption value of viewing posts	Calibration
α	Cost of viewing unshareable content	Calibration
η	Cost of sharing a post	Calibration
$\{p_i^t\}$	Inherent taste for toxic content	Assumption
$\{q_i^t\}$	Probability of being assigned toxic content	Assumption
$\{s_i^t\}$	Probability of sharing toxic content	Model Inversion

Notes: This table shows the parameters of the structural model and the measurement approaches.

Table H.11: Decomposition of treatment effect on toxic shares, expressed as percentage of row totals

a	Contribution of N (views)	Contribution of S/N (shares to views ratio)	Contribution of s^t (probability of sharing)	Total treatment effect on S^t
0.00	0.00	0.00	100.00	100.00
0.20	100.82	0.03	-0.85	100.00
0.60	100.09	0.03	-0.12	100.00
0.80	99.49	0.03	0.46	100.00
1.00	98.54	0.03	1.46	100.00

Notes: This table shows the decomposition of the treatment effect on toxic shares, expressed as percentage of the row totals, for the average user, for different levels of randomization in user feeds, denoted by a . The treatment effect on toxic shares is decomposed into three components: the contribution of the number of toxic posts viewed (N), the contribution of the shares to views ratio (S/N), and the contribution of the probability of sharing toxic content (s^t). The total treatment effect on toxic shares is 50%.

I Algorithms

In this Appendix, I provide details on the algorithms used to simulate a simple recommendation algorithm. I also simulate the treatment using this illustrative personalization algorithm. This builds intuition on how the treatment was implemented in practice. Finally, this Appendix also details the calibration of the model parameters, by using method of matching moments.

I.1 Simulate Control and Treatment Algorithms

Algorithm 1 Simulating Control and Treatment Embeddings

- 1: **Input:** $num_control_users$, $num_treatment_users$, num_movies , $embedding_dim$, num_days
- 2: **Output:** $final_control_embeddings$, $final_treatment_embeddings$
- 3: Generate synthetic binary user-item ratings data with missing values:
 - Ratings are $\{1, 0, \text{NaN}\}$ with probabilities $\{0.3, 0.3, 0.4\}$
- 4: Remove rows with only NaN values
- 5: Calculate the global mean rating excluding NaN values
- 6: Fill in the missing values with the global mean
- 7: Apply Singular Value Decomposition (SVD) to derive embeddings:
 - $U, \sigma, Vt = svds(ratings_filled, k = embedding_dim)$
 - $initial_control_embeddings = U \cdot \sigma$
- 8: Initialize daily control and treatment embeddings arrays:
 - $control_embeddings = zeros(num_control_users, embedding_dim, num_days)$
 - $treatment_embeddings = zeros(num_treatment_users, embedding_dim, num_days)$
 - $control_embeddings[:, :, 0] = initial_control_embeddings$
- 9: Calculate $control_mean$ and $control_var$ from $initial_control_embeddings$
- 10: Set $radius = 2 \cdot \sqrt{\sum control_var}$
- 11: **for** day in 0 to $num_days - 1$ **do**
- 12: **if** day > 0 **then**
- 13: Update control embeddings based on new "usage" with some noise
- 14: $control_embeddings[:, :, day] = control_embeddings[:, :, day - 1] + normal(0, 0.1, shape)$
- 15: **end if**
- 16: **for** user in 0 to $num_treatment_users - 1$ **do**
- 17: **while** True **do**
- 18: Generate a random point uniformly from the epsilon ball
- 19: **if** $\text{norm}(point) \leq radius$ **then**
- 20: $treatment_embeddings[user, :, day] = control_mean + point$
- 21: **break**
- 22: **end if**
- 23: **end while**
- 24: **end for**
- 25: **end for**
- 26: Aggregate the daily embeddings to get the final treatment and control embeddings:
 - $final_treatment_embeddings = \text{mean}(treatment_embeddings, axis = 2)$
 - $final_control_embeddings = \text{mean}(control_embeddings, axis = 2)$
- 27: Plot results

I.2 Comparative Statics

Algorithm 2 Compute and Plot Smoothed Values of N , NS , and fs

- 1: **Input:** Constants θ , α , β , δ , ν , and μ values between 0 and 1 as μ_{values}
- 2: **Output:** Smoothed values of N , NS , and fs
- 3: **Control Regime:** Set $vs_{control} = \mu_{values}$
- 4: **Treatment Regime:** Set $vs_{treatment} = 0.5$
- 5: **Define Functions:**
- 6: **Function to calculate fs :**

$$\text{calculate_fs}(\mu, vs) = (vs/\mu)^\theta \cdot \mu$$

- 7: **Function to calculate N :**

$$\text{calculate_N}(\delta, \theta, \alpha, \nu, \beta, \mu, vs) = \frac{-\alpha \cdot \delta \cdot \theta \cdot \ln((vs/\mu)^\theta \cdot \mu/vs)^2 + \alpha \cdot \delta \cdot (-1 + \theta) \cdot \ln((vs/\mu)^\theta)^2 + \beta \cdot \nu}{2 \cdot \alpha \cdot \nu}$$

- 8: **Function to calculate NS :**

$$\text{calculate_NS}(\delta, \theta, \alpha, \nu, N, \mu, vs) = \frac{\delta \cdot \theta \cdot (-1 + \theta) \cdot \ln(\mu)^2 - 2 \cdot \delta \cdot \theta \cdot \ln(vs) \cdot (-1 + \theta) \cdot \ln(\mu) + \delta \cdot \theta \cdot (-1 + \theta) \cdot \ln(\mu)^2}{2 \cdot \alpha + 2 \cdot \nu}$$

- 9: Compute $N_{control}$ for each μ in μ_{values} and corresponding vs in $vs_{control}$ using CALCULATE_N
- 10: Compute $NS_{control}$ for each N , μ , and vs in $N_{control}$, μ_{values} , and $vs_{control}$ using CALCULATE_NS
- 11: Compute $fs_{control}$ for each μ and vs in μ_{values} and $vs_{control}$ using CALCULATE_FS
- 12: Compute $N_{treatment}$ for each μ in μ_{values} and corresponding vs in $vs_{treatment}$ using CALCULATE_N
- 13: Compute $NS_{treatment}$ for each N , μ , and vs in $N_{treatment}$, μ_{values} , and $vs_{treatment}$ using CALCULATE_NS
- 14: Compute $fs_{treatment}$ for each μ and vs in μ_{values} and $vs_{treatment}$ using CALCULATE_FS
- 15: **Apply LOWESS Smoothing:**
- 16: **Function to smooth data:**

`smooth_data(x, y, frac)` → Apply LOWESS smoothing to x and y with fraction $frac$

- 17: Smooth $N_{control}$ and $N_{treatment}$ using SMOOTH_DATA
 - 18: Smooth $NS_{control}$ and $NS_{treatment}$ using SMOOTH_DATA
 - 19: Smooth $fs_{control}$ and $fs_{treatment}$ using SMOOTH_DATA
 - 20: Plot the Results
-

I.3 Calibration

Algorithm 3 Parameter Optimization Using Moment Matching (Part 1)

Require: Data: vs_data, fs_data, N_data, NS_data, mu_data

Require: Initial Parameters: $\alpha, \beta, \delta, \nu$

Require: Constants: θ

Ensure: Optimized Parameters: $\alpha^*, \beta^*, \delta^*, \nu^*$

Load data from CSV file into variables: vs_data, fs_data, N_data, NS_data, mu_data

Sample data to reduce computation time (e.g., 10% random sample)

Compute empirical means and variances:

$$\text{empirical_means} = [\mathbb{E}[\text{vs_data}], \mathbb{E}[\text{fs_data}], \mathbb{E}[\text{N_data}], \mathbb{E}[\text{NS_data}]]$$

$$\text{empirical_vars} = [\text{Var}(\text{vs_data}), \text{Var}(\text{fs_data}), \text{Var}(\text{N_data}), \text{Var}(\text{NS_data})]$$

function CALCULATE_FS(v_s, μ, θ)

Ensure positive values for v_s and μ :

$$v_s \leftarrow \max(v_s, 10^{-9}), \quad \mu \leftarrow \max(\mu, 10^{-9})$$

Return:

$$f_s = \left(\frac{v_s}{\mu} \right)^\theta \mu$$

end function

function CALCULATE_N($\delta, \theta, \alpha, \nu, \beta, v_s, \mu$)

Ensure positive values for v_s and μ :

$$v_s \leftarrow \max(v_s, 10^{-9}), \quad \mu \leftarrow \max(\mu, 10^{-9})$$

Compute terms:

$$\text{term1} = -\alpha\delta\theta \left(\log \left(\frac{v_s}{\mu} \right) \right)^2, \quad \text{term2} = \alpha\delta(1-\theta) \left(\log \left(\frac{v_s}{\mu} \right) \right)^2$$

Return:

$$N = \frac{\text{term1} + \text{term2} + \beta(\alpha + \nu)}{2\alpha\nu}$$

end function

Algorithm 4 Parameter Optimization Using Moment Matching (Part 2)

function CALCULATE_NS($\delta, \theta, \alpha, \nu, N, v_s, \mu$)

Ensure positive values for v_s and μ :

$$v_s \leftarrow \max(v_s, 10^{-9}), \quad \mu \leftarrow \max(\mu, 10^{-9})$$

 Compute terms:

$$\text{term1} = \delta\theta(1-\theta)(\log(\mu))^2, \quad \text{term2} = -2\delta\theta(1-\theta)\log(v_s)\log(\mu), \quad \text{term3} = \delta\theta(1-\theta)(\log(v_s))^2$$

Return:

$$NS = \frac{\text{term1} + \text{term2} + \text{term3} + \frac{N}{\nu}}{2\alpha + 2\nu}$$

end function

function OBJECTIVE($\alpha, \beta, \delta, \nu$, empirical_means, empirical_vars, vs_data, mu_data)

 Increment call counter

 Compute N values:

$$N_values \leftarrow [\text{calculate_N}(\delta, \theta, \alpha, \nu, \beta, v_s, \mu) \mid \forall (v_s, \mu) \in (\text{vs_data}, \text{mu_data})]$$

 Compute NS values:

$$NS_values \leftarrow [\text{calculate_NS}(\delta, \theta, \alpha, \nu, N, v_s, \mu) \mid \forall (N, v_s, \mu) \in (N_values, \text{vs_data}, \text{mu_data})]$$

 Compute f_s values:

$$fs_values \leftarrow [\text{calculate_fs}(v_s, \mu, \theta) \mid \forall (v_s, \mu) \in (\text{vs_data}, \text{mu_data})]$$

 Compute simulated means and variances

$$\text{simulated_means} \leftarrow [\mathbb{E}[\text{vs_data}], \mathbb{E}[fs_values], \mathbb{E}[N_values], \mathbb{E}[NS_values]]$$

$$\text{simulated_vars} \leftarrow [\text{Var}(\text{vs_data}), \text{Var}(fs_values), \text{Var}(N_values), \text{Var}(NS_values)]$$

 Compute mean and variance differences

$$\text{mean_diff} \leftarrow \sum (\text{empirical_means} - \text{simulated_means})^2$$

$$\text{var_diff} \leftarrow \sum (\text{empirical_vars} - \text{simulated_vars})^2$$

Return objective function value:

$$\text{objective_value} \leftarrow \text{mean_diff} + \text{var_diff}$$

end function

Set **initial guess** for the parameters: $[\alpha, \beta, \delta, \nu] \leftarrow [\frac{1}{4}, 50, 50, 1]$

Optimize the parameters using the Nelder-Mead method:

result $\leftarrow \text{minimize}(\text{objective}, \text{initial_guess}, \text{args} = (\text{empirical_means}, \text{empirical_vars}, \text{vs_data}, \text{mu_data}), \text{method} = \text{NelderMead})$

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Extract optimized parameters:

$$\alpha^*, \beta^*, \delta^*, \nu^* \leftarrow \text{result.x}$$