Can Privacy Technologies Replace Cookies? Ad Revenue in a Field Experiment

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Abstract

As regulators seek to balance user privacy with publisher sustainability, Google's Privacy Sandbox offers a potential replacement for third-party cookies. This paper presents the first independent estimates of the publisher-side economic effects of Privacy Sandbox, a suite of privacy-enhancing technologies for online advertising. Leveraging an open, industry-wide field experiment, we partner with a major ad management firm to evaluate over 200 million ad impressions across more than 5,000 publishers. We find that removing third-party cookies reduces publisher revenue by 29.1%, while Privacy Sandbox preserves just 4.2% of this lost revenue. We further document that Privacy Sandbox increases ad latency and reduces impression delivery by 2.9%. The results underscore the continued economic tension between privacy and the funding of online content.

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Policymakers face a persistent dilemma: how to restrict cross-site tracking without undermining the digital advertising revenues that fund the open internet. Tracking enables the data-driven advertising that underpins a roughly $750 billion global industry and sustains independent publishers. Yet removing tracking risks cutting their revenues and concentrating ad spending within dominant platforms, thereby reshaping global information flows [1]. Industry and regulators have turned to privacy-enhancing technologies (PETs) as a potential path forward, but their economic performance remains largely untested. Using data from over 5,000 publishers in a large-scale, regulator-supervised field experiment, we find that disabling cookie-based tracking lowers publisher ad revenue by about 30%, while PETs recover only 4% of that loss.

Third-party cookies lie at the center of this tradeoff. They enable both ad targeting and measurement, increasing the value of advertising for advertisers and publishers alike. Yet critics liken cookie-based tracking to corporate surveillance. Regulators around the world have responded with strict consent requirements and billions of dollars in fines, while some browsers have blocked third-party cookies by default. These interventions strengthen privacy but reduce publisher income and clutter the web with confusing consent dialogs. The result is a web that is more private, less profitable, and often more frustrating to navigate.

In response, the advertising industry turned to PETs as a compromise. These technologies aim to preserve the essential functions of cookies while reducing data leakage, using techniques such as on-device processing and differential privacy already used in research and government settings. In digital advertising, the challenge is greater: PETs must function at the scale of billions of ad impressions each day across a diverse ecosystem of advertisers, publishers, and intermediaries. Efforts by major tech firms (Apple, Mozilla, Microsoft, and Google) illustrate both promise and risk, yet the economic viability of these tools at ecosystem scale remains uncertain.

Google's Privacy Sandbox was the most ambitious of these initiatives and provided a rare opportunity to evaluate PETs at scale. By building PETs directly into Chrome, Privacy Sandbox aimed to support key advertising functions without exposing users' browsing histories. Most online ads today are selected through real-time auctions using third-party cookies that allow advertisers to target individual impressions. In contrast, the Sandbox's Protected Audience API runs auctions on the user's device, selecting relevant ads based on locally stored interest data. Its Attribution Reporting API enables advertisers to measure whether an ad led to a purchase or other valuable action using noisy, privacy-preserving signals. Chrome launched the Sandbox initiative in 2019 alongside plans to phase out third-party cookies and made the technologies generally available in 2023.

Yet because Google built and controlled the Sandbox, its rollout raised significant competition concerns. Regulators worried that the Sandbox could tilt the market toward Google's own services, prompting a formal investigation by the UK Competition and Markets Authority (CMA). These concerns are amplified by Chrome's two-thirds share of global browser traffic and Google's substantial market presence across the ad-tech ecosystem. At the same time, regulators acknowledged PETs as a promising route toward compliance and privacy-risk reduction. The central question was how Sandbox would perform once deployed in the open market. To answer this question, the CMA and Google jointly supervised a market-wide field experiment testing the market impact of the cookie phase out and the Privacy Sandbox rollout. We partnered with a leading ad-tech intermediary to provide novel and independent evidence on the economic impact of PETs on online publishers.

Our analysis shows that PETs offered limited revenue recovery for publishers, constrained by low adoption and latency challenges. Although these factors contributed to Google's 2025 decision to halt cookie deprecation and retire the Sandbox, the patterns we document also highlight opportunities for improvement. Broader adoption and targeted technical refinements could make privacy-enhanced advertising more economically viable. Together, these findings inform ongoing PET development and the policy efforts needed to balance privacy, competition, and the long-term sustainability of the open web.

An Open Approach to Policy Evaluation

To inform this policy debate, the CMA and Google designed an open, industry-wide field experiment **(year?)**. Chrome randomly assigned users to one of three environments: (1) the status quo with cookies, (2) Privacy Sandbox with cookies disabled, and (3) a fully cookieless setting. This design enables an ecosystem-wide causal evaluation of both the economic cost of removing cookies and the effectiveness of Privacy Sandbox as a replacement. Unlike prior studies based on observational data, or experiments limited to a single firm [3], our analysis offers ecosystem-wide experimental evidence.

The experiment is remarkable for its openness: browser-facing firms can observe each user's assigned treatment group and evaluate the resulting ad outcomes. This transparency sets a precedent for regulators seeking credible evidence before approving large-scale platform changes. Unlike platform disclosures released after the fact, the CMA-Google experiment enabled independent evaluation by a wide range of industry stakeholders. The CMA received 25 tester submissions from firms representing diverse segments of the ad ecosystem, including Google itself **(year?)**. Among these, our analysis provides the first independent evidence on publisher revenue impact. Although the Privacy Sandbox program has since been retired, the CMA–Google experiment remains a landmark model for open platform evaluation.

Calls for greater transparency in platform governance have produced mixed results. Some jurisdictions, like the European Union, have enacted laws that require data access for vetted researchers. Separately, some platforms have collaborated with academic researchers and even released privacy-protected datasets publicly [5]. Yet privacy risks and commercial incentives still constrain data access. The CMA–Google experiment offers a rare alternative: a publicly observable field test open to external analysis and scrutiny. The model offers a promising path for future oversight in digital markets and counters criticism that platform-led research is often opaque or selectively shared [6].

Despite its strengths, the CMA–Google experiment reveals Sandbox's performance under only partial industry adoption. Because implementing Sandbox tools is costly, most ad-tech firms adopted only some components—or none at all. In August 2024, roughly 17% of sites ran on-device Sandbox auctions, and 13% added users to interest groups for off-site targeting [7]. Limited adoption places a ceiling on performance: the Sandbox can boost publisher revenue only if ad buyers use these tools at scale. Google offered incentives to spur participation, but adoption remained limited. Even so, the CMA–Google experiment offers regulators the strongest available evidence on how Privacy Sandbox performs in practice.

We leverage the open experiment using data from Raptive, the largest ad-management company in the online display ecosystem. Online display advertising involves real-time auctions for individual ad impressions, coordinated through a complex chain of intermediaries that represent both publishers and advertisers. Many publishers outsource this process to ad management companies like Raptive, which manage the technical and business complexity of selling ad inventory. Raptive oversees ad monetization for over 5,000 publishers, providing a comprehensive view of publisher-side advertising outcomes. In August 2024, Raptive served more than 200 million ad impressions to Chrome users participating in the CMA-Google experiment, spanning a wide variety of sites and content types. These data allow us to assess how cookie removal and Privacy Sandbox affect real-world publisher revenue.

Economic Cost of Removing Cookies

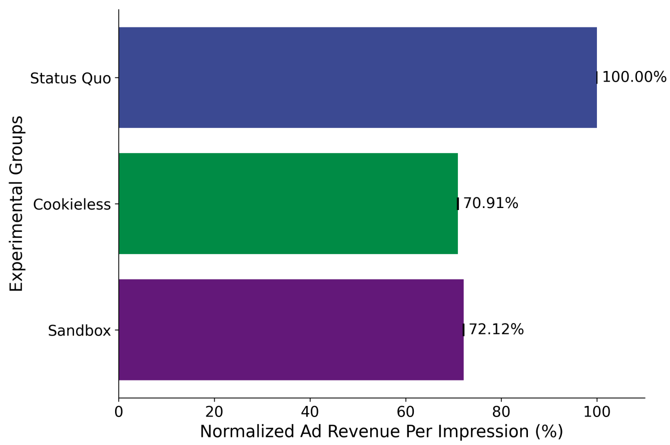
To assess what Privacy Sandbox must replace, we first estimate the incremental revenue publishers gain from third-party cookies. Cookies underpin digital advertising because they support ad measurement and targeting. By connecting ad views to online purchases, cookies solve the classic "eyeballs-to-wallets" problem that plagued traditional media like television and billboards. Cookies also help advertisers recognize users on other sites to retarget past visitors to the advertiser's site.

The widespread use of cookies has also made them central to privacy reform. While Safari and Firefox blocked third-party cookies in 2018 and 2019, Chrome announced a similar plan in 2019 but reversed course in April 2025. Nevertheless, many Chrome impressions already lack cookies because of site-level opt-outs, cache clearing, or browser settings. In our data, 21.8% of Chrome impressions are cookieless, and when combined with Safari and Firefox traffic, an estimated 36% of global browser traffic already lacks third-party cookies.

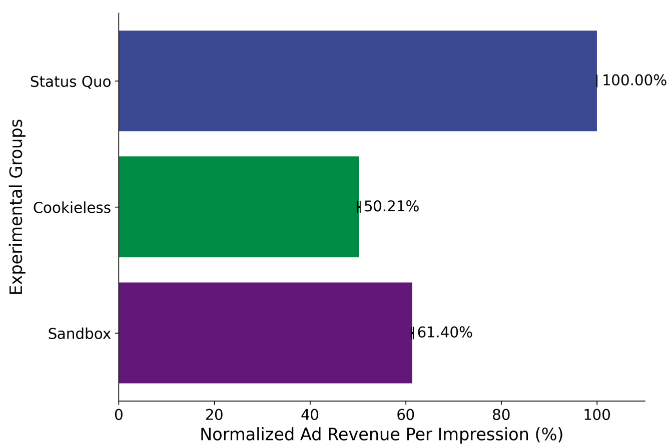
To mitigate these losses, publishers and ad-management firms such as Raptive use alternative identifiers that partially restore targeting and measurement functions. These substitutes are less powerful than cookies because their adoption is fragmented, but they nonetheless temper the revenue impact we observe.

Using the CMA–Google experiment, we estimate that disabling third-party cookies reduces publisher revenue by 29% relative to the status quo (see the figure, top, and tab. S2). Because the status quo group already includes some cookieless traffic, this estimate understates the isolated effect of cookie removal (see tab. S2). Our estimates are smaller than prior research, which often reports revenue declines over 50% [3, 8], likely reflecting Raptive's extensive use of alternative

Figure 1: **Privacy Sandbox recovers a small share of ad revenue lost from disabling cookies** The open experiment reveals publishers' mean ad revenue with third-party cookies (Status Quo), without cookies (Cookieless), and with Privacy Sandbox in the absence of cookies (Sandbox). The top figure presents overall findings. The bottom figure shows evidence from EU users, who face greater regulatory restrictions on cookies. EU revenue is more dependent on third-party cookies though Privacy Sandbox recaptures more of the lost revenue from eliminating cookies. Both figures include bars indicating 95% confidence intervals.



(a) All impressions



(b) EU user impressions

Note: The normalized ad revenues are calculated by dividing each experimental group's mean scaled ad revenue by that of the Status Quo in tab. S1. For the Sandbox group, we use the mean ad revenue adjusted to account for unsold impressions.

identifiers.

Revenue losses are especially pronounced in the European Union. For EU users, publisher revenue falls by 50%, compared with 29% overall (see the figure, bottom, and tab. S4). Stricter privacy rules mean that a larger share of EU traffic is already cookieless in the status quo (see tab. S4), which should temper measured losses. Instead, the sharper decline likely reflects Raptive's more limited use of alternative identifiers in the EU because of privacy restrictions.

Taken together, these results highlight the stakes: cookies remain critical to publisher revenue, and current patchwork substitutes cannot fully replace them. For policymakers weighing stricter privacy rules, our findings suggest that the economic cost of a complete phaseout of cross-site identifiers would be substantially larger than what we observe here.

Limited Gains from Privacy Sandbox

Privacy Sandbox aims to replace cookies with privacy-preserving tools, but its revenue performance falls short. In our experiment, it recovers only 4.2% of the revenue lost when third-party cookies are removed (see tab. S2). Publisher revenue in the Sandbox condition falls by 27.9% relative to the status quo—only slightly better than the 29.1% decline under full cookie removal (see the figure, top, and tab. S2).

Limited industry adoption constrains Sandbox performance, complicating policy evaluation. In our data, only 7% of impressions in the Sandbox group are sold via Protected Audience API, with just four ad-tech buyers participating. We therefore examine markets with higher adoption to assess whether stronger uptake improves performance.

Adoption is somewhat higher in the European Union, where stronger regulatory pressure encourages firms to view Sandbox tools as compliance-friendly alternatives. There, 12% of impressions were sold through Sandbox's on-device auctions: more than twice the U.S. share of 4.9%. As a result, Sandbox recovers a greater share of the revenue lost from cookie removal (22.5%, see tab. S4). Even so, total publisher revenue falls by 38.6 percent (see the figure, bottom, and tab. S4).

Technical design also contributes to these weak results. Sandbox runs ad auctions directly in the browser, competing alongside traditional auctions, which introduces meaningful delays. As a result, ads in the Sandbox group often take more than twice as long to load as cookie-based auctions (see fig. S2a). Latency is especially severe when impressions are sold through on-device auctions (see fig. S2b). These lags cause some users to scroll away or exit before an ad appears, leaving roughly 3% of impressions unsold. If latency were eliminated, we estimate that Sandbox revenue recovery would rise from recovering 4% to about 11%.

Other participants in the CMA–Google experiment reported somewhat better results [4, 9], and Google's own analyses found smaller revenue declines **(author?)** [10]. In particular, advertisers reported smaller performance gaps, implying that if Google had phased out cookies, stronger buy-side adoption of Sandbox tools might have translated into higher publisher revenues. Still, the gap between Sandbox outcomes and the value provided by third-party cookies remains wide for publishers. Closing this gap would have required both broader industry buy-in and technical improvements that reduce latency. Google began addressing these issues in late 2024 by improving on-device auctions to reduce latency. Without such technical progress and broader buy-in, Sandbox ultimately fell short of providing a viable economic substitute for cookies.

Policy Paths to Sustainable Privacy

Our findings point to a clear policy lesson: PETs hold some promise, but their success depends on regulatory clarity, technical refinement, and broader adoption. PETs offer a middle path between pervasive user tracking and blunt privacy restrictions, reducing data leakage while preserving core advertising functions. Yet PETs face resistance on multiple fronts. Industry stakeholders doubt their performance, while fragmented regulatory systems often lack the mandate or incentives to support compromise solutions. Even where regulators view PETs as useful compliance tools, concerns about data leakage and opaque implementation have limited regulatory endorsement. This ambivalence stalls uptake, even in contexts where privacy risks are most acute and regulatory clarity most needed.

Our findings, alongside those of other testers [4], informed Google's decision to abandon its plan to replace cookies with Privacy Sandbox. The episode underscores the difficulty of aligning privacy, performance, and competition goals in digital markets. Privacy Sandbox illustrates both the potential and the challenges of PETs in this setting: ambitious in scope, but constrained by limited adoption and early-stage effectiveness. Like all infrastructure, PETs require iteration.

Latency, adoption, and performance can improve, but progress depends on rigorous, real-world testing.

The CMA–Google experiment shows how open, collaborative testing can serve as a model for regulation. Unlike internal platform reports, this model allows external stakeholders to observe, analyze, and challenge outcomes, thereby building trust in new technologies. As regulators confront complex platform design choices, this experimental approach offers a path toward more effective and accountable innovation.

Although Privacy Sandbox has been retired, the policy challenges it exposed persist. Regulators should focus on three priorities. First, clarify their stance on PETs to either promote or slow adoption, for example by easing consent requirements for PET-based advertising. Second, intervene when conflicting mandates between privacy and competition authorities block workable compromise solutions. Third, expand open experiments like the CMA–Google test beyond the initial testing phase to track technological progress and to identify scaling issues as adoption grows.

Our study provides independent, large-scale experimental evidence on how cookie removal and Privacy Sandbox affect publisher revenue, quantifying the economic trade-offs between tracking and PETs. These results inform policy and advance the broader economics-of-privacy literature. Because our data capture early-stage adoption, they may understate Sandbox's potential. As privacy regulation evolves, continued open testing will be essential to understanding how PETs can scale sustainably.

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Supplementary materials

Materials and Methods

Background: Privacy Sandbox

The transition away from third-party cookies marks a foundational change in digital advertising. While Safari and Firefox disabled cookies by default in 2018 and 2019, respectively, Chrome announced plans to follow suit in 2019 but reversed course in April 2025. Despite this reversal, an estimated 36% of global browser traffic already lacks third-party cookies, as a substantial share of Chrome traffic operates without them.[1] Third-party cookies support cross-site tracking, which enables behavioral targeting, retargeting, and ad measurement. Beyond advertising, cookies also support user authentication, content personalization, and fraud prevention.

In response to growing privacy concerns, Google introduced Privacy Sandbox—a suite of privacy-preserving technologies intended to substitute for cookies while retaining core advertising functionality. Privacy Sandbox offers technologies for targeting (Topics, Protected Audience), measurement (Attribution Reporting), and fraud prevention (Private State Tokens). These tools leverage privacy-enhancing techniques such as on-device processing, differential privacy, and zero-knowledge proofs, which verify information without disclosing underlying data. For example, the Topics API enables interest-based targeting by assigning users to coarse-grained topic categories based on recent browsing activity. The Protected Audience API (PA API) enables on-device auctions for behavioral advertising and retargeting. Specifically, advertisers enroll visiting users into PA API "interest groups" and define bidding strategies, while publishers trigger on-device auctions in the browser, selecting ads without revealing cross-site user data. Finally, the Attribution Reporting API offers privacy-preserving conversion measurement by adding noise.

Chrome began testing these technologies in 2021 and made them generally available in 2023. In August 2024, adoption remained modest: 27.8% of sites called the Topics API, 16.6% ran Protected Audience auctions, and 13.3% added users to Protected Audience interest groups to show targeted

[1] Chrome traffic can lack third-party cookies due to user actions such as site-level opt-outs, clearing cookie caches, or enabling browser-level blocking. In our data, 21.8% of impressions lack cookies—though this is a conservative estimate, as it reflects only users who have not disabled cookies in their browser settings. Using StatCounter's August 2024 global browser market share data, we estimate that at least 36% of traffic lacks third-party cookies—comprising all Firefox (2.74%), Safari (18.57%), and 21.8% of Chrome (65.20%) traffic. See: https://gs.statcounter.com/browser-market-share.

ads off-site [7]. Google plays a central role in deploying Sandbox technologies. In August 2024, Google's market share was 21.5% in Topics API calls, 38.3% in Protected Audience interest group creation, and 88.7% in Protected Audience auctions. Raptive also participated and ranked fourth in interest group creation with a 7.9% share.

Privacy Sandbox led a broader industry shift towards privacy-enhancing ad technologies. Microsoft is piloting a targeting solution in its Edge browser (Ad Selection API) modeled on the Protected Audience API.[2] The World Wide Web Consortium (W3C), spurred by a joint proposal from Firefox and Meta,[3] is advancing a browser-based measurement standard [11]. Apple continues to evolve its own measurement tool, AdAttributionKit. Among these efforts, Privacy Sandbox represented the most comprehensive in scope and functionality, and most broadly adopted to date.

In October 2025, Google announced it would retire most Privacy Sandbox technologies including Topics API, PA API, and Attribution Reporting API. In its place, Google announced that Chrome favors the W3C's proposed interoperable Attribution standard [11].

Experimental design

The Privacy Sandbox field experiment was jointly developed by Google and the UK's Competition and Markets Authority (CMA), the lead regulator overseeing Chrome's privacy-related changes. Launched in January 2024, the experiment encompasses 2% of eligible Chrome users—approximately 60 million users—across desktop and Android mobile devices [2, 4]. Users are randomly assigned to one of three groups: (1) 1% in Status Quo (third-party cookies enabled), (2) 0.75% in Privacy Sandbox (Sandbox APIs active and cookies disabled), and (3) 0.25% in Cookieless (both APIs and cookies disabled).[4] Chrome assigns users to groups at the browser level and makes these assignments visible to websites and ad tech firms, enabling coordinated participation from both publishers (supply side) and advertisers (demand side) in the experiment. This enables general equilibrium evaluation across many firms in a live market setting.

To ensure consistent treatment exposure, Chrome imposes several eligibility criteria. Users must run a recent version of Chrome that supports Privacy Sandbox and the experimental labels,

[2]Source: https://learn.microsoft.com/en-us/microsoft-edge/web-platform/ad-selection-api.

[3]Source: https://blog.mozilla.org/en/mozilla/privacy-preserving-attribution-for-advertising.

[4]Google and the CMA instead refer to these groups as control_1, treatment_1, and control_2 respectively. For additional technical explanations on the testing labels, see https://developers.google.com/privacy-sandbox/private-advertising/setup/web/chrome-facilitated-testing.

and cannot be in incognito mode or have manually disabled cookies. The design also excludes both Chrome Enterprise users and iOS users. While Chrome enforces assignment via technical implementation, users retain partial control. They may override cookie settings or disable Privacy Sandbox. Those in Sandbox and Cookieless groups receive a one-time notification about enhanced tracking protection but the notice does not identify their assigned group.

Experimental validity

We evaluate the internal validity of the experiment by examining the balance of observations and covariates across experimental groups. Our analysis excludes subgroups exhibiting clear imbalances due to bot activity or other reasons. After filtering, remaining observations display only economically small differences across treatment groups.

We identify several sources of potential imbalance. We exclude Unix-based users, a common source of bot traffic identified in prior analyses of the experiment.[5] We also drop impressions from outdated Chrome versions (v119 and earlier), which exhibit minor imbalances. Despite efforts to filter bot traffic, some residual bot activity is expected in an open experiment on the web. Ad latency, which varies by treatment group, introduces small causal differences in the number of successfully loaded impressions (see Figure 2)—our unit of analysis.

Table 5 shows that the Status Quo, Privacy Sandbox, and Cookieless groups include 104.5M, 76.3M, and 26.4M impressions respectively. These closely match the expected randomization shares of 1%, 0.75%, and 0.25%,[6] although the Sandbox group falls short (−2.85%) of its counterparts. We interpret the shortfall in Sandbox impressions relative to expected counts as the causal impact of Privacy Sandbox on the share of sold impressions (see Equation 6).

Table 6 displays covariate balance by user device and region. Differences are small among sold impressions. These are likely driven by longer ad latency in the Sandbox group, which reduces impression delivery. The latency effects are more severe on mobile, which may explain the slight over-representation of desktop impressions in the Sandbox group.[7]

[5] This issue is discussed in **(author?)** [12] and here: https://github.com/WICG/turtledove/issues/982.

[6] The Status Quo group slightly under-delivers (−0.22%) and the Cookieless group slightly over-delivers (+0.66%) relative to the average of these two "control groups." These discrepancies may reflect longer ad rendering times for impressions with third-party cookies. However, the differences are small enough that we retain our assumption from Section that the Status Quo and Cookieless group impression counts represent the number of impression opportunities.

[7] The gap between the median latency in the Sandbox and Status Quo groups is 0.41 seconds on desktop, 1.41 seconds

Although statistically significant given the large number of observations, these differences are economically small and likely reflect treatment-induced differences in ad delivery. Taken together with the covariate and group-size balance checks, we view the data as consistent with proper randomization. The CMA reached the same conclusion based on balance checks using non-public user-level data—such as page load counts—provided by Google [4].

Data

We analyze a proprietary dataset from Raptive containing 207.2 million ad impressions served to experimental users in August 2024. Raptive manages ad monetization for over 5,000 publishers, providing a broad view across the online display ad ecosystem. These data span 44 content categories—including entertainment, food, gaming, and news. Impressions span desktop (40.8%), mobile (56.8%), and tablet (2.4%) devices, with 60.9% served to users in the U.S. and 6.7% in the EU.

Raptive is well positioned to assess the impact of Privacy Sandbox. Raptive interfaces directly with users and can observe browser-assigned group labels without relying on upstream intermediaries—avoiding potential data gaps that could bias inference. By capturing all impressions served and revenue earned across conditions, Raptive offers a comprehensive and internally valid estimate of publisher-side effects.

We apply two additional filters to ensure accurate measurement of revenue in the Privacy Sandbox condition. First, we focus on August 2024, when Google began fully reporting PA API revenue to Raptive.[8] Second, we restrict attention to banner ads and exclude native and video formats, which were not yet supported by PA API.

Third-party cookie use is exclusive to the Status Quo group, though only 78.1% of Status Quo impressions contain third-party cookies. Eligible Chrome users in the experiment permit cookies at the browser level, but may lack cookies because of site-level consent, cache clearing, or browser extensions.

In the Sandbox group, we observe limited use of Privacy Sandbox technologies. 7.2% of im-

on smartphones, and 1.82 seconds on tablets.

[8]Prior to August 2024, Google's ad server (Google Ad Manager) excluded PA API impressions where a non-Google seller won the meta-auction, so the data was incomplete: see https://support.google.com/admanager/answer/14639079.

pressions are sold via PA API. This low share reflects competition between the on-device auction and the conventional ad auction. For Topics API, we obtain an indicator for whether Raptive observes a behavioral category label for a given impression. Vendors like Raptive can query the Topics API for a user's interest categories, but the browser returns a topic label only if the vendor previously encountered the user on a site associated with that topic. This design limits vendors from inferring new user interests they would not have known under the cookie-based system. Raptive observes Topics API category data for 27.1% of impressions in the Sandbox group. Google is present on Raptive-affiliate websites as well as a wider network of sites [7], so 27.1% represents a lower bound on how often Google observes Topics API category data. We do not observe Attribution Reporting API or Trust Token API usage, although these may be functioning in the background.

Outcomes

We consider two publisher outcomes: ad revenue and ad latency. To preserve confidentiality, ad revenue is expressed in U.S. dollars as cost per thousand impressions (CPM) and scaled by a factor between 0.1 and 1. As a result, we present most revenue comparisons relative to the mean in the Status Quo group. Ad latency—the time between an ad request and its delivery—affects both user experience and monetization.

Estimation methodology

We use the experimental design to estimate intent-to-treat (ITT) effects for two interventions: (1) removing third-party cookies and (2) replacing cookies with Privacy Sandbox technologies. Let i denote an impression, $D \in \{SQ, PS, CL\}$ the treatment group, and y the outcome (ad revenue or latency). The ITT effects respectively are defined as:

$$ITT_{CL} = E[y_i|D_i = CL] - E[y_i|D_i = SQ] \tag{1}$$

$$ITT_{PS} = E[y_i|D_i = PS] - E[y_i|D_i = SQ] \tag{2}$$

To assess the degree to which Privacy Sandbox mitigates revenue loss from cookie removal, we compute what we term the *recovery share*. This metric reflects the percentage of cookie-driven revenue that Privacy Sandbox is able to recover.

$$\text{Recovery share} = \frac{E[y_i|D_i = PS] - E[y_i|D_i = CL]}{E[y_i|D_i = SQ] - E[y_i|D_i = CL]} \tag{3}$$

The Status Quo group includes both cookied and cookieless impressions. Since only impressions with third-party cookies generate additional revenue in the Status Quo group, the ITT estimate underestimates the effect of cookie removal. To recover the effect specific to cookied traffic, we estimate the average treatment effect on the treated (ATET):

$$ATET_{CL} = \frac{ITT_{CL}}{\Pr\left[Cookie_i = 1|D_i = SQ\right]} \tag{4}$$

where $Cookie_i$ is an indicator for whether impression i has a third-party cookie (see e.g., [13]). Thus, the ATET scales the ITT by the inverse share of cookied impressions in the Status Quo group. Note that we do not estimate an analogous ATET for Privacy Sandbox, since the technologies are designed to apply regardless of cookie availability.

While most quantities in the above expressions can be directly estimated using sample counterparts, missing data in the Privacy Sandbox condition presents a challenge. Longer ad latency—especially under the Protected Audience API—may cause users to navigate away before the ad loads. In these cases, no ad is served and no revenue is generated. Our dataset contains only sold impressions, so these instances represent missing outcomes. To address this, we use the law of iterated expectations:

$$\begin{aligned} E\left[y_i|D_i = PS\right] =& E[y_i|D_i = PS, sold_i] \cdot \Pr\left[sold_i|D_i = PS\right] \\ &+ E[y_i|D_i = PS, unsold_i] \cdot \left(1 - \Pr\left[sold_i|D_i = PS\right]\right) \end{aligned}$$

Because unsold impressions yield zero revenue, the group-level mean simplifies to the mean for sold impressions multiplied by the probability of a sale:

$$E\left[y_i|D_i = PS\right] = E[y_i|D_i = PS, sold_i] \cdot \Pr\left[sold_i|D_i = PS\right] \tag{5}$$

We estimate the Sandbox sale probability ($\Pr[sold_i|D_i = PS]$) by leveraging the known randomization probabilities and assuming all impressions are observed in the Status Quo and Cookieless groups. Given the experimental design—1% of users assigned to Status Quo, 0.25% to Cookieless, and 0.75% to Privacy Sandbox—we expect the Privacy Sandbox group to have $\frac{3}{5}$ as many total impression opportunities as the combined Status Quo and Cookieless groups $\left(\widehat{N^0_{PS}} = \frac{3}{5}(N_{SQ} + N_{CL})\right)$. Thus, we estimate the Sandbox sale probability as the ratio of the total (observed) impressions (N_{PS}) and the total (implied) impression opportunities $\left(\widehat{N^0_{PS}}\right)$:

$$\widehat{\Pr}[sold_i|D_i = PS] = \frac{N_{PS}}{\widehat{N^0_{PS}}} = \frac{N_{PS}}{\frac{3}{5}(N_{SQ} + N_{CL})} \tag{6}$$

This correction enables a more accurate comparison of Sandbox monetization performance by adjusting for unsold impressions.

Heterogeneous treatment effects

We explore heterogeneity in ad revenue by publisher size (see table S3) and geographic region (see table S4). To explore whether effects vary by firm size, we use impression volume as a proxy for publisher size and divide publishers into quartiles. Prior privacy economics research often finds that smaller firms are more vulnerable to privacy restrictions than larger firms [14]. This analysis explores the potential unintended competitive effects of cookies restrictions and Privacy Sandbox. We also examine variation by user location, comparing the U.S., the EU, and other regions. We focus on the U.S., which accounts for 60.9% of impressions, and the EU, which offers a contrasting policy environment. The EU enforces stricter consent requirements under the General Data Protection Regulation (GDPR), leading to greater cookieless traffic and potentially greater resulting Sandbox adoption.

Table 1: Ad Revenue by Experimental Group (Adjusted for Unsold Impressions)

	Mean estimate	Standard error
Status Quo		
Scaled ad revenue	0.440	1.17×10^{-4}
Cookieless		
Scaled ad revenue	0.312	2.36×10^{-4}
Privacy Sandbox		
Scaled ad revenue (conditional on sold)	0.327	1.36×10^{-4}
Unsold impression share[a]	2.85%	-
Adjusted ad revenue (all impression opportunities)[b]	0.317	1.32×10^{-4}

Note: Scaled ad revenue is expressed in CPM (cost per thousand impressions), multiplied by a confidentiality factor between 0.1 and 1. [a]We derive the share of unsold impressions using Equation (6) and the group-level impression counts from Table 5. [b]For the Sandbox group, adjusted ad revenue accounts for unsold impressions due to latency using Equation (5) and the share of unsold impressions. Asymptotic standard errors given for means.

Supplementary Text

A Additional Exhibits

Table 2: Treatment Effect Estimates

	Estimate	Standard Error
Effect of Removing Cookies		
Intent to Treat	-29.09%	0.057%
Share of impressions with cookies (Status Quo)	78.09%	0.0040%
Average Treatment Effect on the Treated	-35.29%	0.062%
Effect of Privacy Sandbox		
Intent to Treat	-27.88%	0.036%
Recovery Share	4.18%	0.20%

Note: The Intent-to-Treat effects are calculated using Equations (1) and (2), and expressed as percentage changes relative to the mean revenue in the Status Quo group. The ITT estimate for Privacy Sandbox adjusts for unsold impressions. The Average Treatment Effect on the Treated is obtained using Equation (4) and normalized by the estimated mean ad revenue of *cookied* impressions in the Status Quo group (0.465). The recovery share is computed using Equation (3). Standard errors are heteroskedasticity-robust. For the ATET, robust standard errors are computed using two-stage least squares. The delta method is used to account for normalization in all estimated effects.

Table 3: Treatment Effect Estimates: Publisher Size Heterogeneity

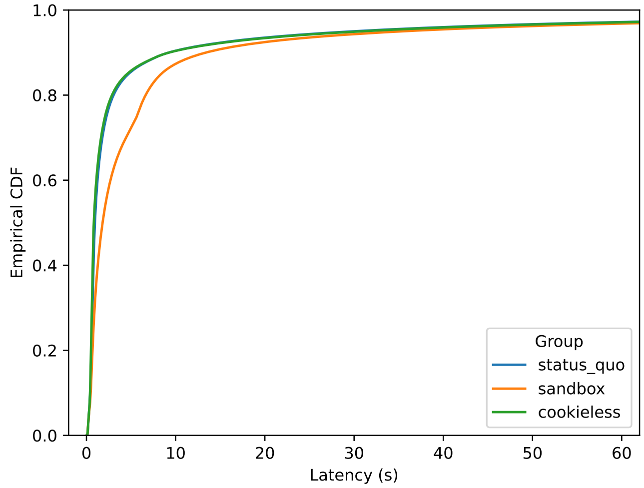
	Publisher size			
Effect of Removing Cookies	Small	Medium	Large	Very large
Intent to Treat	-36.21%	-36.70%	-34.19%	-28.61%
Share of impressions with cookies	77.20%	77.80%	77.58%	78.14%
Average Treatment Effect on the Treated	-43.81%	-44.85%	-41.99%	-34.67%
Effect of Privacy Sandbox				
Intent to Treat	-34.36%	-33.84%	-32.90%	-27.40%
Recovery Share	5.12%	7.78%	3.78%	4.23%

Notes: Publisher size is determined by impression volume and split into four size quartiles.

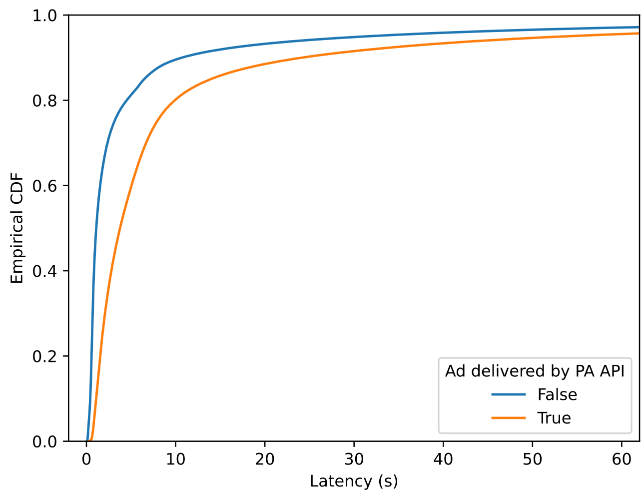
Table 4: Treatment Effect Estimates: Country Heterogeneity

Effect of Removing Cookies	EU	US	Remaining countries
Intent to Treat	-49.79%	-26.93%	-45.25%
Share of impressions with cookies	56.61%	80.58%	77.80%
Average Treatment Effect on the Treated	-66.43%	-32.61%	-55.35%
Effect of Privacy Sandbox			
Intent to Treat	-38.60%	-26.29%	-40.67%
Recovery Share	22.47%	2.37%	10.12%

Notes: Remaining countries include all non-U.S. and non-EU geographies.



(a) Ad Latency by Experimental Group



(b) Sandbox Group: Ad Latency by PA API Delivery

Figure 2: Empirical CDFs for Ad Latency

Table 5: Observation Counts by Treatment Group

Group	Randomization Probability	Impression Counts	Deviation from Controls†
Status Quo	1%	104,510,637	-
Privacy Sandbox	0.75%	76,283,492	-2.85%
Cookieless	0.25%	26,363,067	-

Notes: †Deviation from controls refers to the group's percentage deviation from the average number of impressions in the Status Quo & Cookieless groups, given the randomization probabilities (see Equation (6) for calculation). Note that we exclude the Privacy Sandbox from this comparison as we expect that the Privacy Sandbox has a causal effect of reducing the number of impressions sold.

Table 6: Covariate Balance by Devices and Regions

	Status Quo	Privacy Sandbox	Cookieless
Device Types			
Desktop	40.25%	41.56%	40.96%
Smartphone	57.37%	56.10%	56.62%
Tablet	2.38%	2.35%	2.42%
Countries & Regions			
EU	6.65%	6.79%	6.76%
US	61.13%	60.66%	61.01%
Others	32.24%	32.55%	32.22%

Notes: Sold impression shares by experimental group.