Navigating Cookie Consent Violations Across the Globe

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Abstract

Online services provide users with *cookie banners* to accept/reject the cookies placed on their web browsers. Despite the increased adoption of cookie banners, little has been done to ensure that cookie consent is compliant with privacy laws around the globe. Prior studies have found that cookies are often placed on browsers even after their explicit rejection by users. These inconsistencies in cookie banner behavior circumvent users' consent preferences and are known as *cookie consent violations*. To address this important problem, we propose an end-to-end system, called ConsentChk, that detects and analyzes cookie banner behavior. ConsentChk uses a formal model to systematically detect and categorize cookie consent violations. We investigate eight English-speaking regions across the world, and analyze cookie banner behavior across 1,793 globally-popular websites. Cookie behavior, cookie consent violation rates, and cookie banner implementations are found to be highly dependent on region. Our evaluation reveals that consent management platforms (CMPs) and website developers likely tailor cookie banner configurations based on their (often incorrect) interpretations of regional privacy laws. We discuss various root causes behind these cookie consent violations. The resulting implementations produce misleading cookie banners, indicating the prevalence of *inconsistently implemented and enforced* cookie consent between various regions.

1 Introduction

One of the most common ways of collecting data from users' web browsers is through the use of cookies. Cookies are used to remember users' preferences, transmit information such as location or IP addresses, and track users' browsing history. However, the collection and use of personal data through cookies have raised significant privacy concerns. In response to these concerns, regions/countries worldwide have enacted laws requiring disclosure of privacy practices and/or user consent for data collection. For instance, the EU's General

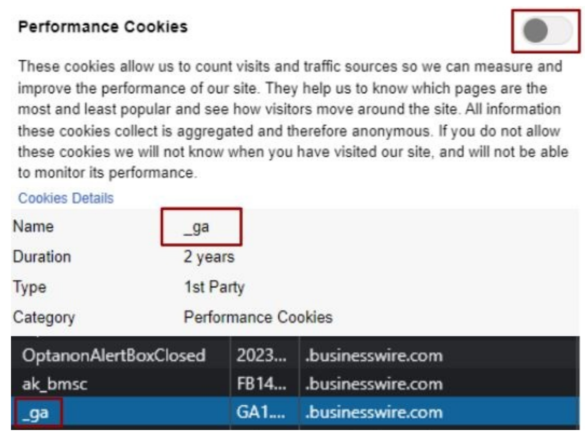


Figure 1: A cookie banner menu allows users to set their consent/rejection of cookies. However, the website fails to honor the users' consent (e.g., Google Analytics).

Data Protection Regulation (GDPR) [65] and ePrivacy Directive (ePD) [64] suggest online services obtain consent before collecting personal data for advertising. Similarly, the California Consumer Privacy Act (CCPA) in the U.S., Canada's Personal Information Protection and Electronic Documents Act (PIPEDA), and Singapore's Personal Data Protection Act (PDPA), are among other similar privacy regulations that provide guidelines on consent, online behavioral advertising (OBA), and tracking cookies. These policies reflect a global shift towards enhanced data privacy protections.

To comply with these regulations, websites employ mechanisms and third-party services known as *Consent Management Platforms* (CMPs) to allow users to manage their cookie preferences. Figure. 1 illustrates an example of rejecting cookies from Google Analytics. Despite these measures, prior research indicates that cookies are often placed on browsers even after users have explicitly rejected them through cookie settings interfaces [9, 45]. These inconsistencies in cookie banner behavior circumvent users' consent preferences and are known as *cookie consent violations* or cookie violations. Such practices not only undermine user trust but may also go against regional privacy guidelines [8, 16, 25].

These observations prompt three critical questions:

1. *How pervasive are cookie consent violations?*
2. *Do cookie banners, behaviors, and violations vary across different regions with distinct privacy regulations?*
3. *Why do these discrepancies in cookie behaviors occur?*

We address these questions by conducting a comprehensive cross-country analysis of cookie consent practices. We examine websites across 8 English-speaking regions with varying privacy regulations—Ireland (EU), the United Kingdom (UK), California, USA (CA), Michigan, USA (US), Canada (CAN), South Africa (ZA), Singapore (SG), and Australia (AU)—to understand how cookie consent mechanisms are implemented and whether they are consistent with users' choices and regional privacy laws. We have designed and deployed a cookie consent measurement and auditing tool called `ConsentChk` that automatically interacts with cookie banners. We use this tool to analyze cookie consent and CMPs on websites across these 8 regions worldwide.

`ConsentChk` addresses several technical challenges in detecting cookies that violate user consent. It detects and activates cookie banners' menus, setting the consent choice for each cookie (accept/reject), and checks for inconsistencies in the expected and observed behavior. We conduct an evaluation analyzing cookie consent behavior for the same set of websites across different regions with different regulatory privacy frameworks. Using `ConsentChk`, we have examined 1,793 websites from the 20k top global websites according to the Tranco list [42].

From these measurements, we found widespread occurrences of cookie consent violations across all 8 regions. Websites exhibited higher rates of violations in certain regions than others. Our analyses indicate that cookie consent is *inconsistently implemented and enforced* in all regions. By studying the occurrence of cookie consent violations in these regions, we uncover several potential root causes. In particular, due to how cookie consent libraries are implemented, the number of cookies and violations is highly dependent on location. The ability to reject consent for a particular cookie depends on whether a CMP decides to support privacy laws via a template.

This paper makes the following contributions:

- An end-to-end measurement tool, called `ConsentChk`, that crawls websites, detecting infringements on users' consent preferences for each cookie on a website. `ConsentChk` uses an approach that identifies features of cookie banner buttons to activate the cookie banner menus of any website automatically. The detection of cookie consent violations has a high precision of >91%. (Sections 4 and 4.6)
- A study on 1,793 of the top visited websites in the globe based on the Tranco 1M list [42] with cookie banners. `ConsentChk` detected that 96.18% (EU) – 97.72% (US) of websites across all regions contain at least one cookie consent violation. These violations primarily occur in the form of undeclared cookies or ignored cookie rejections, demonstrating that cookie banners and CMPs have inadequate coverage and correctness. (Sections 5 and 6)
- The discovery of discrepancies in cookie consent behavior across various regions. We observe that, compared to the EU, the same websites in the US have an average of almost 12 additional cookies, and an average of 10 additional cookie consent violations. Similarly, regions like Canada, Singapore, South Africa, and Australia with their own privacy frameworks have 6-8 more cookies and 5-7 more cookie consent violations than the EU. (Section 6)
- An analysis of the potential root causes behind cookie consent violations and regional discrepancies. CMPs provide banner customization and geolocation rulesets. Thus, cookie banner buttons and cookie behaviors are largely reliant on factors such as location, advertiser interest, cookie scraping/classification accuracy, and more. (Section 7)

2 Background

2.1 Privacy Laws Across the Globe

Privacy laws generally provide rules for how data controllers/processors and businesses should process data. These laws also establish and define the following criterion required for: (1) establishing consent of data processing given by the subject, (2) defining what types of data fall under this protection (usually personal data, identifiers, and/or cookies). Several privacy laws like the GDPR and CCPA are also applied in an extraterritorial manner to Europeans and Californians who use non-European and non-Californian services.

GDPR (European Union, EU). Consent is one of 6 lawful bases defined in the GDPR for processing data. The others include a contractual obligation, a legal obligation, vital interests, a task in public interest, and legitimate interests. Many websites provide a privacy policy or notice for the data they process under these other 5 bases (for purposes such as marketing, fraud prevention, etc.), but additionally provide a cookie banner for obtaining consent for the usage of cookies. Article 7 of the General Data Protection Regulation (GDPR) discusses informed consent related to the processing of users' personal data. In particular, Article 7.3 states that data subjects can withdraw their consent at any time and that it should be as easy to withdraw as to give consent [30].

DPA (United Kingdom, UK). The UK's Data Protection Act (DPA) is similar to GDPR, following and adapting the same protection rules to the UK's legal system [18, 48, 50].

CCPA (California, CA). Some privacy laws, such as the California Consumer Privacy Act (CCPA) do not require consent for data processing. Unlike the GDPR, a lawful basis for processing data is not required, however, businesses cannot process data in unfair or deceptive manners. Instead, this framework requires that businesses meeting certain criteria (large amount of revenue from selling personal information,

Region	Law	Relevant Articles and Sections	E.T.	Consent	Personal Information Definition
EU	GDPR	Articles 3, 4, 7, 21, 82.1, Recital 30, 32	Yes	Informed	Info About Person, Includes Cookies, Identifiers
UK	DPA	Section 57, 99	Yes	Informed	Info About Person, Includes Cookies, Identifiers
CA (US)	CCPA	Section 1798.120, 1798.140.aj, 1798.145.a1G, 7026.h	Yes	Implied	Any Unique ID, Includes Cookies, Identifiers
MI (US)	None	None	None	None	None
CAN	PIPEDA	Schedule 1, Principle 3 (4.3.8), Sec 1.6.1	Yes [1]	Informed	Info About Person, Includes Cookies, Identifiers
ZA	POPIA	Sections 3.1(b), 5(d)-(e), and 11(3)-(4), Ch. 1	No	Informed	Info About Person, Identifiers
SG	PDPA	Part 4 Division 1.16, Part 6 Division 26.1	Yes	Implied	Identifiers, Includes Cookies/OBA
AU	APP	APP 5.1, 6, 7	No	Required	Identifiers

Table 1: A brief high-level overview of region-specific privacy frameworks and their requirements. The E.T. column indicates whether there is an extra-territorial scope. Identifiers include IP, location, targeting cookies, biometrics, derivable identity, etc.

with certain exemptions) give consumers information about data collection activities and purposes in a "notice at collection" [14], giving users the right to access, delete, and opt out of the selling of their data.

PIPEDA (Canada, CAN). Canada's Personal Information Protection and Electronic Documents Act (PIPEDA's) applies to organizations that collect, use, or disclose personal information in the course of a commercial activity. Fair Information Principle 3 states organizations must generally obtain express consent when the information being collected, used, or disclosed is sensitive [33, 52].

POPIA (South Africa, ZA). Similarly to the GDPR, the Protection of Personal Information Act (POPIA) identifies 5 legal bases for processing data, including consent from the data subject. It requires organizations to obtain consent before collecting and processing personal information. Additionally, data subjects have the right to be notified of data collection, request correction, destruction, or deletion, and to object to processing of data for marketing [40, 41].

PDPA (Singapore, SG). The Personal Data Protection Act (PDPA) states in Part 4, Division 1 that an organization must not use or disclose personal data about an individual unless the individual gives, or is deemed to have given, his/her consent to the collection, use, or disclosure. It also states that users may at any time withdraw any consent given in respect of the collection, use, or disclosure by that organization of personal data about the individual [51].

APP (Australia, AU). Section 5.1 of the Australian Privacy Principles (APP) requires entities to disclose purposes and request consent at or before the time or, if that is not practicable, as soon as practicable after, collecting personal information about an individual. Section 6 requires entities to not use or disclose the collected personal information for another purpose without consent [55, 63].

2.2 Role of Cookie Consent in Privacy Laws

While consent is one of many frameworks for allowing users to control and understand privacy practices, it is the primary form of control used for cookies on websites, due to the prevalence of cookies in online behavioral advertising. In Europe, the ePrivacy Directive (ePD) was an EU directive which modernized privacy laws to apply to cookies [64]. Cookies (other than those used for strictly necessary services) required user consent. These new guidelines paved the way for the IAB's Transparency and Consent Framework (TCF) to be created [29]. The TCF is a voluntary standard providing publishers (websites) and advertisers (vendors) with tools and libraries for providing and managing consent options for users.

Due to the extra-territoriality clause of privacy laws like GDPR and CCPA, companies are required to comply with laws so long as they do business with any EU or CA resident. Website developers cannot be expected to handle privacy compliance with so many regions outside of their own company's location. As such, intermediary 3rd-party consent management platforms (CMPs) have standardized compliance for website developers. Based on the provisions put forth in the various regions worldwide, these CMPs convert *interpretations* of privacy laws into *implementations* of privacy laws. These CMPs have standardised frameworks for regional privacy laws, directly impacting website developers' cookie banner implementations. CMPs manage users' consent, which are important for compliance with GDPR in Europe, PIPEDA in Canada, CCPA in California, and more. Hence, CMPs are often implemented such that the geolocation from a user's browsing session informs the CMP to display a particular cookie banner with its UI and behavior customized to the region's regulations [60]. For example, in Europe, users more frequently encounter detailed consent banners with guidelines set by the GDPR, ePD, and TCF, whereas in the U.S., banners may only notify users of data collection practices, or simply not appear at all.

Work	Violations	Legal Def.	Non-CMP	U.I.	P.I.	Subpages	# V.P.	# Sites	# Crawls
Our Work (2025)	✓	✓	×	✓	✓	✓	8	1,793	10
Bollinger (2022)	✓	✓	×	×	×	✓	1	29,398	1
Rasaii (2023)	×	×	×	×	×	✓	8	513	5
Kancherla (2024)	✓	×	×	✓	×	×	1	161	1
Matte (2020)	✓	✓	×	×	×	×	5†	1,426	1
Sanchez-Rola (2019)	✓	✓	×	✓	✓	×	3†	2,000*	1
Liu (2023)	✓	✓	×	×	✓	×	2	100,000*	8
Van Eijk (2021)	×	×	×	✓	×	×	18†	603	1
Bouhoula (2024)	✓	✓	✓	✓	×	✓	1	48,843	1
Papadogiannakis (2021)	✓	×	✓	×	✓	×	1	27,953*	3

Table 2: Comparison of related work. † indicates measurements from vantage points with overlapping legal jurisdiction and * indicates inclusion of sites that do not have cookie banners. Ours is the first to measure violations from various legal jurisdictions. Measurement Methodologies: U.I. – User interfaces, P.I. – Personal information, V.P. – Vantage points.

2.3 Related Work

Prior studies have focused on three main topics for cookie consent: (1) automating or exercising cookie banner UIs, (2) analyzing cookie declarations, behavior, and enforcement, and (3) legal and usability analyses of consent mechanisms.

Cookie Banner UI Automation. Browser extensions such as Consent-O-Matic and Autoconsent automate rejection by matching CSS/JS patterns. These programs use handcrafted CSS matchers and JavaScript object models to create a JavaScript model of consent notices and automatically set the cookie banners to rejection. Ad blockers' "annoyance blocking" closes/hides banners but does not actively reject cookies. Sweepatic's platform detects non-consensual cookies but only before a consent choice being made [62]. Several researchers study the effectiveness of these automated opt-outs such as Khandelwal *et al.* [39] which model consent dialogs as seq2seq tasks and Demir *et al.* [27] which compares 6 tools over 98k pages from 30k sites.

Cookie Declarations, Behavior & Enforcement. Cookie compliance has been studied since the GDPR's enforcement in 2018. Sanchez-Rola *et al.* [56] manually analyzed 2,000 sites across EU, USA, China, and other regions, reporting that 92% perform tracking before consent and only 2.5% erase cookies after their placement. They also report that cookie-settings interfaces appear on just 16% of EU sites and 12% of US sites. Matte *et al.* [45] also analyzed 1,426 EU sites using IAB TCF banners, finding that 54% contained violations like pre-selected options, consent stored pre-choice, etc. These findings were extended to 3rd-party cookies as well by Kancherla *et al.* [38], who inspected 1,200 sites (top 200 for UI, 1,000 random from top 5k), reporting that 74% do not inform third parties of rejection. Cookies that remain on the browser were also found to be continually used even after rejection. Liu *et al.* [43] compared advertiser bidding before and after GDPR/CCPA opt-out (across 4 CMPs and 34 IPs) and found negligible differences in tracking.

Scaling Cookie Violation Measurements. Bollinger *et al.* [9] and Bouhoula *et al.* [10] focused on CMP compliance, defining 8 violation types (e.g., undeclared cookies and implicit consent) and scaled up compliance testing to 30k and 97k sites in the EU, respectively. The former found at least one violation in 94.7% of sites, with 82.5% sites containing undeclared cookies and 69.7% sites with implicit consent, and the latter similarly found 65.4% were likely to collect data despite negative consent.

Cookie Banners Across Regions. Measurement studies have also been conducted on cookie banners in regions worldwide. Van Eijk *et al.* [28] crawled 1,543 sites from 18 countries (27,488 measurements in total) and found that the odds of seeing a cookie banner are 102% higher in the EU. Rasaii *et al.* [54] examined 518 sites across 8 locations (Sweden, Germany, US West/East, Brazil, South Africa, Australia, India), finding cookie banners in 47% in EU vs. 30% non-EU.

Legal Requirements & Usability Studies. Santos *et al.* [57] identified 22 legal requirements for valid consent (e.g., free, specific, informed, prior, revocable) and showed that no CMP satisfies them all. Santos *et al.* [58] also determined that CMPs act as both data controllers/processors, noting that HTTPS-based CMP s cripts process IP addresses (an identifier) and shape users' choices. Bouma-Sims *et al.* [11] performed a usability study of OneTrust's UI across US and UK participants, finding that over half could not make a properly informed consent decision (52.4% US vs. 46.2% UK).

Comparison of `ConsentChk` with Related Work. Unlike prior studies that focus on a single region, law, or CMP, we measure cookie consent behavior across 8 jurisdictions, 3 major CMPs, and websites from the Tranco top 20k. By analyzing legal regulations and CMP documentation, we identified the root causes that result in cookie banner/consent/placement disparities and violations. We conducted measurements at the individual cookie level, identifying cookies that likely contained personal information. `ConsentChk` is the first to compare cookie consent violations across multiple non-EU regions with privacy laws. Table 2 provides a summary.

3 Definitions and Terminology

We provide formal definitions of cookies, consent preferences, and cookie consent violations in Table 3.

Cookie Banners and Cookie Preference Menus. "Cookie banners" inform users of the use of cookies (providing no option or confirmation only) and allow users to accept, reject, or manage their cookie consent preferences [26]. Cookie banners can appear as pop-ups on landing pages or can be activated by buttons placed in footers or cookie/privacy policy pages. These banners are often hidden and must be manually activated in regions where privacy laws do not require consent before data collection. Oftentimes, these banners allow users to open separate "cookie preference menus" with controls that allow users to set their consent preference on specific cookie categories or individual cookies (Figure. 1). The categories can be specified by purposes and/or by advertising vendors.

Websites collect users' cookie consent preferences and block/unblock cookies locally based on the consent choice. CMPs create and maintain special cookies to record users' consent choices on websites. For example, OneTrust and Cookiebot store users' consent preference in cookies named *OptanonConsent* [49] and *CookieConsent* [24], respectively. Other sites use 1st-party cookie banners instead of CMPs.

Cookie Definitions. Considering a cookie in a browser's cookie storage as a tuple of key–values, `ConsentChk` distinguishes cookies by their *name*, *domain*, and *path*. This distinction of cookies follows the storage model in the cookie specification [6]. Other cookie attributes, while still important to monitor, may change over time even for the same cookie (e.g., *value* and *expiration time*).

A *cookie* represents a value stored on users' browser that can be transferred to a website's server. This data collection of cookies is typically *consistent* with user's indicated consent preference if the user approves and does not reject the cookie. A website correctly enforces a user's consent preference if all of the cookies used on the website are consistent with the users' cookie consent preferences. A *cookie consent preference* is the preference indicated via a user's consent decision to a cookie or category of cookies' usage (e.g., approve or reject advertising cookies).

Cookie Consent Violations. We selected three main forms of cookie consent violations to investigate in this paper. These violations are defined as when cookie consent mechanisms are not consistent in their expected/specified behavior and may mislead users to believing that tracking cookies are not placed on their browsers. These three violations are originally derived by us but are similar in nature and scope to the cookie consent violations explored in Bollinger *et al.*'s work [9].

An *Ignored Cookie Rejection* violation occurs when the website uses a cookie that is rejected and not consented by the user. This behavior is misleading, making users unaware that cookies are still being used to collect their data even after they rejected cookies. Using explicitly rejected cookies could violate a user's consent preference.

Undeclared Cookies prevent users from setting their consent preference for a cookie, so the use of such cookies circumvent the principle of consent being freely-given and a choice. Undeclared cookie consent violations occur when cookies that are not disclosed by the CMP or cookie banner appear on the user's browser. The Undeclared Cookies violation is different from the *unclassified* cookie category (frequently used by CMPs like Cookiebot) which still informs users of the usage of the cookies in this category.

A *Wrong Cookie Category* violation is when the cookie's consent is accepted and rejected at the same time. This occurs when the categories of cookie banners overlap, allowing a cookie to be both rejected and approved by a user. For example, a cookie could be included in both the Strictly Necessary and Targeting categories. A user could have rejected targeting cookies but accepted strictly necessary cookies. This is akin to contradictory statements in privacy policies identified by the FTC and prior studies [4, 12, 53].

The existence of Ignored Cookie Rejections and Undeclared Cookies seemingly violate the GDPR, as Recital 32 states that the conditions for consent require that "consent should not be regarded as freely given if the data subject has no genuine or free choice or is unable to refuse or withdraw consent without detriment". In Canada, PIPEDA guidelines state that consent is reasonable for online behavioral advertising if individuals are aware, informed of these practices and are easily able to opt out. The guidelines also state "If an individual is not able to decline the tracking and targeting...then organizations should not be employing that type of technology for online behavioral advertising [33]." Similar articles exist in other privacy frameworks like PDPA and others.

Note that while these cookie consent mechanisms may be inconsistent with privacy laws and guidelines, they may not violate the laws. Rather, they demonstrate inconsistent behavior from the implementations provided by CMPs. In reality, "consent" is broadly defined and may differ from region to region (e.g., GDPR allows 5 other lawful bases beyond consent). A thorough review of prior legal cases and court rulings may be required to determine whether these "violations" actually breach any laws or regulations.

Term	Definition	Logical Description
Cookie	Defined by (name, n; domain, d; path, p)	$c = \{n, d, p\}$
Cookie Equivalence	Two cookies (name, n; domain, d; path, p) match	$c_1 \equiv c_2, \iff n_1 = n_2 \wedge d_1 = d_2 \wedge p_1 = p_2$
Cookie Consent Preference	Pair of cookie and consent choice	$P = \{c_i, s_i\}$ where $s_i \in \{consent, \neg consent\}$
Approved Cookies	Accepted	$A_c = \{c \mid (c,s) \in P \wedge s = consent\}$
Rejected Cookies	Rejected	$R_c = \{c \mid (c,s) \in P \wedge s = not\_consent\}$
Compliant Cookie Use	Cookie used consistently with consent choice	$Compliant \iff c \in A_c \wedge c \notin R_c$
Ignored Cookie Rejection Violation	Cookie used inconsistently with consent choice	$IgnoredReject \iff c \notin A_c \wedge c \in R_c$
Undeclared Cookies Violation	Cookie used without appearing in cookie library	$Undeclared \iff c \notin A_c \wedge c \notin R_c$
Ambiguous Cookie Category Violation	Cookie in a rejected + accepted category	$Ambiguous \iff c \in A_c \wedge c \in R_c$.

Table 3: All definitions relevant to cookie consent and cookie consent violations.

4 Crawler System Design

4.1 Overview

Detecting cookie consent violations requires automatically setting cookie consent and activating the cookie banners and consent preference menus. This remains challenging due to the diversity of HTML implementations of consent banner menus. Additionally, depending on the region, cookie banners and menus may need to be manually activated them.

Several tools have automated the interactions with consent notices [31, 47, 68]. Khandelwal *et al.* [39] click every element and then detect cookie banner menus after each click. Bollinger *et al.* [9] accept/reject cookie consent by using the GDPR-specific Consent-O-Matic tool [68]. However, these approaches are less thorough and scalable than what is needed for our evaluation. We wish to audit cookie behavior after setting consent for individual categories, as well as auditing cookie banners that do not pop up.

To remedy this deficiency, `ConsentChk` activates cookie banner menus by using a *cookie-button extractor* (Section 4.3) and a *menu activator* (Section 4.4). When accessing a web page, if a cookie banner menu is not detected, the extractor analyzes HTML elements to extract the candidate cookie banner buttons that may activate a menu. Cookie consent preferences are extracted in two steps: (1) cookie-category consent and (2) cookies in each category. Finally, cookie consent violations are detected and classified (Section 4.5).

4.2 Implementation Details

To extract the set of cookies during a website visit, `ConsentChk` extracts the cookies sent to servers via the network debugging functionality of Chrome DevTools Protocol that reports all HTTP(S) requests with associated cookies [36]. Dynamic analysis is advantageous because it reveals "real" occurrences of cookies rather than finding only potential ones, thus reducing false positives. For example, a website may block the use of 3rd-party cookies by preventing the loading of 3rd-party scripts and frames without removing the cookies. This additional analysis overcomes the limitations of prior works that extract all cookies in the browser regardless of whether cookies were actually transferred to servers [56].

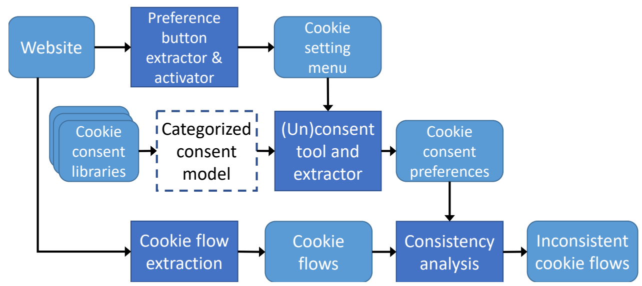


Figure 2: `ConsentChk` analyzes a website by activating the cookie preference menu and auditing cookie behavior. The dashed box represents an one-time manual step that creates a reusable consent setter for each consent library.

We posit that a website should enforce a cookie consent preference and remove/prevent cookie placement if (1) the consent choice is recorded in the browser, (2) the cookie matches, and (3) the web page being visited is within the scope of consent. These conditions ensure the consent preference of a cookie applies only when the user browses the web pages to which the user gave their consent preference. For example, the user's consent preference given to website *a.com* does not apply to website *b.com*, although it applies to subdomains like *subpage.a.com*. `ConsentChk` maps the cookie declarations in the cookie banners to the cookies used by the website by matching cookie names and domains. For patterns such as *_gaxxx* or *_ga###*, we assume an 'x' or '#' to match any single character. However, a single '#' at the end of the declaration matches any alpha-numeric string. For example, the declared cookie name "_gatxxx" matches cookie "_gat123". The scope of a consent preference is defined by the domain of the consent cookie (such as *OptanonConsent* of OneTrust) or other local storage object which records the user's consent. Similarly, the domain names of a cookie and a declaration match each other if the declared domain is a suffix of the cookie domain. This domain matching scheme is similar to the standard cookie domain matching specification [6].

4.3 Preference Button Extractor

To increase the coverage of `ConsentChk` beyond websites using consent libraries, we create a detector for extracting cookie banner buttons. We define a *cookie banner button* to be an HTML element that, upon a user click, displays a menu for the user to set the cookie consent. For each web page, the cookie-button extractor finds visible HTML elements that represent a button or link in all *iframes* contained in the page. We consider *a*, *button*, *div*, and *span* elements which are commonly used to represent links and buttons [15, 44]. For *div* elements, we only select leaf elements to avoid unrelated elements. `ConsentChk` uses a random forest model with feature groups such as n-grams and keywords from HTML attributes such as aria-label, class, id, and inner text. To increase its coverage, the activator attempts to click the top k candidate buttons. Specifically, if clicking a non-cookie button navigates to another page or activates no consent preference menus, `ConsentChk` returns to the initial URL and tries other buttons. Additional details regarding the datasets, annotation process, classification features, performance metrics, and models used for our cookie button extractor can be found in Appendix A.

4.4 Cookie Consent Exerciser

Since CMPs commonly group consent settings into cookie categories to simplify the consent process, we derive a *categorized consent* analysis framework that groups cookies into categories and provides the list of cookies of each group. We divide (by purposes or vendors, for example) the set of cookies used on a website into subsets, called *cookie categories* t_k. A consent preference of cookie category t_k applies to all cookies in that category. For example, the consent rejection of *krxd.net* domain cookie category applies to all cookies from that domain.

Automatic (Un)consent Tool. To analyze a specific cookie banner instance, its UI controls need to be mapped to the components in the analysis framework. The main manual effort is to map the HTML elements to the corresponding cookie consent categories. We use the Chrome DevTools to identify CSS selectors that uniquely identify UI elements on the layout. Although the identification of the mapping is done manually, we need this manual mapping only once for each of the limited number of cookie banners' layouts.

Cookie Consent Preference Extractor. After setting the user's consent preference on the UI, to extract the consent preference of each cookie recorded by the cookie library, we extract the consent preference for each category and the list of cookies for each category. Combining these two lists, we get the consent for each individual cookie. For example, OneTrust stores consent preferences of categories in the *OptanonConsent* cookie and the lists of cookies per cookie category in *en.json*. Compared to Consent-O-Matic, which does not support extraction of states that requires UI inputs, our tool can measure previously unmonitorable inconsistencies of OneTrust.

4.5 Cookie Consent Violation Classifier

Each cookie is then monitored and classified using the logical rules set in Table 3. Cookies that are placed even after the tool rejects cookies are classified as Ignored Cookie Rejection Violations. Cookies placed without being declared in the cookie library set by the CMP are Undeclared Cookie Violations. These violations are classified based on the actions performed by the cookie consent exerciser and the cookies declared in the CMPs' cookie libraries.

4.6 System Evaluation

We perform a small-scale end-to-end evaluation of `ConsentChk`'s detection of cookie consent violations and measure the occurrences of each cookie-violation type. We also analyze the performance of `ConsentChk` for ambiguous mappings from cookie declarations to browser cookies.

We evaluate the precision of detecting Ignored Cookie Rejection, Undeclared Cookies, and Wrong Cookie Category violation types by manually rejecting cookie consent on the websites. We randomly selected validation sets of 40, 40, and 30 websites with each of these violation types detected in a crawl of the top 20k websites. We chose to evaluate a small subset of websites with violations since each site required manual verification. We visited each website, rejected cookies, and visited sub-pages using a clean Chrome browser instance. The accepted/rejected cookie consent preferences and the transferred cookies were recorded by using the DevTools network monitor.

To corroborate the correctness of `ConsentChk`'s detection, we checked whether each rejected cookie with Ignored Cookie Rejection discovered by `ConsentChk` was captured in the manual browsing. Similarly, we checked whether cookies with Undeclared Cookies were unspecified in the cookie banners. We manually checked and discussed ambiguous cases (e.g., cookie names were declared as *_ga_#*), to determine whether the detection was correct. Using the annotations, our results demonstrated that the rule-based detection pipeline has a low false positive rate. We manually reproduced and verified that 92.1% of cookies with Ignored Cookie Rejection, 91.2% with Undeclared Cookies, and 87% with Wrong Cookie Category were detected by `ConsentChk`. We checked the correctness of the detected cookie consent violations using the CMP and sites' storage objects, such as *en.json*. This way, we verified all of the correctly detected violations.

This roughly 90% FPR from manual validation or reproduction likely resulted from some violating cookies not loading (e.g., embedded YouTube video). `ConsentChk` randomly navigates to subpages for loading cookies. We clicked on some random subpages in our manual reproduction, but found the subpages and cookies loaded are not deterministic.

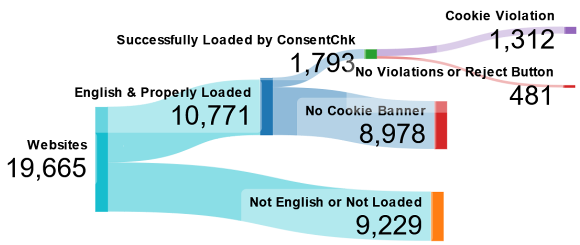


Figure 3: Breakdown of sites evaluated in our study.

5 Measurement Methodology

CMP	Market Share	Cookie List?	Cookie Decl.?
Osano	2.18%	✓	✗
OneTrust	**1.98%**	✓	✓
CookieYes for WP	1.30%	✗	✗
WP CookieNotice	1.21%	✗	✗
Cookiebot	**1.20%**	✓	✓
IAB Europe TCF	1.15%	✗	✗

Table 4: The most popular CMPs with more than 1% market share on the top 1M websites as reported by BuiltWith [13].

Selected CMPs. We report results from the five categories defined by cookie libraries we selected — OneTrust, CookiePro, and Cookiebot— which are some of the most widely used on the Web. Each of OneTrust and Cookiebot has a >1% market share while CookiePro has 0.23%. These CMPs were chosen due to their inclusion of both cookie lists and cookie declarations. Table 4 shows the market shares and the satisfied criteria of the CMPs. Since CookiePro is part of OneTrust, we combine it into the reported results of OneTrust.

The selected CMPs support different cookie categories. The four commonly-supported categories are *Necessary*, *Functional*, *Analytics*, and *Targeting*. While Cookiebot use four fixed cookie categories, OneTrust supports varying cookie categories. For example, *scientificamerican.com* uses *Social Media Cookies*, a customized category of OneTrust. See Appendix B for the decoding of consent choice cookies.

Website Selection. From the top 20k global websites in the Tranco list November 2023 (ID: 5Y3LN), we select 10,436 websites, which have an English homepage and were loaded successfully, for further analysis with `ConsentChk`. Some websites in the list failed to load for various reasons. For example, some URLs are non-website ad-serving domains. The language of the websites is determined by a neural-network-based language detector after converting the web pages to plain text [32, 59].

Measurement Locations. We evaluate the detection performance in regions with privacy regulations that generally require user consent before data collection. We select Ireland, the UK, California, Michigan, Canada, South Africa, Singapore, and Australia, as eight measurement locations. These locations were selected because (1) the websites are displayed in English and (2) they support a privacy framework requiring notices prior to data collection (except Michigan, a US state without CCPA-like privacy laws). We measured the websites from IP addresses by using proxies running on AWS and DigitalOcean, two major cloud providers.

Repeated Measurements. We first performed crawls in all 8 regions on the top 20k websites. Close to 1.8k websites across all regions contained a detected cookie banner. After this initial crawl, we recrawled the union of the sites across all regions 10 times (successfully loaded with cookie banners). Each measurement iteration involved crawling all 8 regions and took roughly 8–12 hours to complete, spanning 1 week to complete the 10 measurements.

5.1 Measurement Procedure

`ConsentChk` first opens a clean web browser instance and visits the homepage of the website under test. It detects a cookie banner button to open the cookie banner menu, using the preference button extractor.

After detecting the cookie banner button, `ConsentChk` rejects the cookie consent, reloads the URL where the cookie consent choices were submitted, and checks the Consent-Enforcement Conditions to ensure that the user's consent choice was recorded. These conditions are defined by the consent library used by the website and specify when a cookie can be set or accessed based on the user's consent preferences.

Next, `ConsentChk` visits other sub-pages that have hyperlinks on the homepage with URLs matching the domain of the consent cookie to generate cookie traffic and check for cookie consent violations. These sub-pages are chosen randomly to ensure a representative sample of the website's content is analyzed. This step is important for capturing additional cookies used on subsites [35]. `ConsentChk` rejects all rejectable cookie categories.

`ConsentChk` uses k=*5* to try the top-5 cookie banner button candidates as a trade-off between coverage and experimentation duration. Each page contains an average of 232 buttons and links, so using only the top 5 links/buttons reduces the experimentation time significantly while still achieving a high recall rate. Raising k forces the system to check all k buttons on the websites that do not contain any cookie banner buttons, which increases the experimentation time significantly.

The crawler uses a 60-second timeout to load the pages. We found this timeout sufficient to completely load most of the web pages with the fast network of our servers and cloud providers. The crawler uses the Playwright browser automation tool [46] to control the Google Chrome web browser and utilizes techniques provided by an automatic browsing plugin to avoid getting detected by bot detection (i.e., Puppeteer and Playwright's stealth mode) [7]. These added Playwright functionalities mimic human behavior, bot flagging via headless detection and user agents.

We conducted experiments in a distributed framework based on Docker Swarm [37] on 4 machines with 1.08TB RAM and 96 task queue workers. The cookie-consent scanning of the 10,436 websites took 40 hours to perform the measurements from the 8 locations. The crawls were performed during October 4–12, 2024.

Of the top 20k websites, 10.8k websites were in English and properly loaded. From this subset, `ConsentChk` found 1,793 websites with cookie banners and consent settings from our list of CMPs. `ConsentChk` analyzed the cookie consent behavior of 1,312 sites containing cookie preference menus (see the breakdown in Figure 3). `ConsentChk` collected information on cookie banner parameters, cookies declared in the CMP, cookies placed on the browser, website traffic and navigated subpages.

5.2 Personal Information Analysis

Most privacy laws only pertain to personal information – that is data that could be used to either identify an individual or data pertaining to an identifiable individual. As we are primarily interested in studying cookie consent violations, we need a method for differentiating cookies containing personal information or identifiers from those not. For example, some cookies may simply contain a number to indicate a user's preference for light/dark mode on a site while other cookies may contain the latitude and longitude of a user or a unique tracking identifier. The cookie declaration may also include its purposes that describe the nature of data usage. For example, the cookie *loc* with domain *addthis.com* collects the location of users to help *addthis.com* track their location when its share buttons are clicked. Because of this and the fact that a vast majority of the cookie consent violation types are Undeclared Cookies, we need a system to detect and categorize whether cookies contain personal information, using the cookie's name, value, and declared purpose. We built a lightweight detector that searches for keywords (e.g., city, postal code, state, country name, and uid) and regex patterns (e.g., IP address, GPS location, and common tracker formats), as well as decoding Base64-encoded cookies. The detector also leverages the zxcvbn [69] library for measuring the entropy of the cookie values (to discover tracking UIDs). For those cookie purposes not declared by website developers in the cookie libraries, our detector referenced Cookiepedia [67] as well as other open-source cookie databases. We opted to use this lightweight approach for detecting personal information to scale our approach to millions of cookies.

Roughly 75% of all cookies found in our measurement likely involve personal information. Regional discrepancies exist as well, with the EU and UK having roughly 3% more cookies including those with personal information than other regions. *Unless stated otherwise, the reported results only include cookies that were detected to have personal information.*

Measurement	1st-Party Cookies		3rd-Party Cookies	
	Levene's	H-Test (p)	Levene's	H-Test (p)
Mean Cookies	4e-6	69.9 (2e-12)	0.0023	71.7 (7e-13)
Ignored Reject	0.0074	73.9 (2e-13)	0.0348	73.3 (3e-13)
Undeclared	6e-5	68.0 (4e-12)	0.0017	70.5 (1e-12)
Wrong Categ.	0.0005	69.7 (2e-12)	0.0002	57.7 (4e-10)

Table 5: Statistical Significance Tests for Figures 4 to 6.

5.3 Analysis Methodology

We analyzed 3 different aspects of cookie banners on the websites across the 8 regions: (1) the cookies placed on each website across each region; (2) the differences in cookie consent violations we detected for each cookie on the websites across each region; and (3) the differences in UI settings and parameters for the websites across each region. We report both high-level trends in cookie consent violations and cookie count as well as per-site and pairwise region differences. In reporting total violation counts (Table 6), we report the union across the 10 measurements. In other plots (Figures 5 and 6), we report the average. *Unless stated otherwise, the reported results use Ireland as a baseline due to the strict requirements on cookies from the GDPR.*

5.4 Statistical Significance Tests

Our analysis includes statistical significant tests, Levene's Test and Kruskal Wallis H Test for testing the (non)homogeneity of variances and for comparing multiple independent samples. In our study, Levene's Test was applied to both first- and third-party cookie counts across the eight regions. As shown in Table 5, all p-values from Levene's Test are less than 0.05 for both first- and third-party cookies, indicating the significantly different variances in cookie counts and violations across regions (non-homogeneous variances).

We then used the Kruskal-Wallis H Test, a non-parametric test that compares the medians of two or more independent groups and is suitable when the assumptions of normality are not met, which was the case for the distribution of cookies and cookie consent violations in the regions we studied. We used this test to determine whether cookie placement and violation measurements were significantly different across regions. Our application of the H test revealed significant H-statistics for all variables analyzed (Table 5) in both first- and third-party cookies, demonstrating statistically significant discrepancies in cookie placement and cookie violation rates between regions.

5.5 Limitations of Our Study

The nature of our measurement methodology accompanies the inherent biases and limitations that may affect the generalizability of our study. These limitations arise from our website/CMP selections, embedded content not deterministically loading in our random crawls, using commercial server IPs as opposed to residential IP addresses, and not studying websites without cookie banners/settings loading. Our website selection may affect the representativeness of our results, given that our measurements cover a fraction of websites (i.e., 20K potential websites and 1.3k that display cookie banners). Our intent is not to claim that all websites and CMPs exhibit these behaviors, but rather to study the subset of sites that deploy popular CMPs.

6 Measurement Results

Many websites did not honor users' preferences on cookie consent. Specifically, we found that 96.18% of websites accessed in the EU contain at least one cookie consent violation. We found that undeclared cookies constituted 47.35% of personal information cookies on websites.

We also discovered that most websites failed to remove cookies on consent rejections. 43.12% of cookies on websites ignored users' cookie consent rejection.

We also detected contradictory cookie banners on 3.13% of websites (Wrong Cookie Category Violation). These cookies had contradictory consent preferences with the same *Name* and *Host* but included in two different categories. For example, *_gid* cookie of *cambridge.org* was listed in both always-active Necessary and rejectable Performance categories.

Websites made it challenging for users to opt out of unnecessary cookies. Despite the Necessary cookie category being designed to indicate cookies required purely for website services, we found 9.81% of websites with un-Necessary cookie categories set unnecessary cookies as "always active." This would prevent users from opting out of tracking practices.

Few websites correctly enforced the user's cookie consent preferences on all cookies. Specifically, only 3.82% of websites correctly enforced the consent preferences of users.

6.1 High-Level Observations

Cookie Consent Violations. In each of the eight regions, at least one cookie consent violation was found to occur in up to 96.18–97.72% of websites. The wrong cookie category violation was detected with the least prevalence, with 218–446 cookies. The undeclared cookies violation was the most prevalent, with 54,633–250,447 cookies.

Consent-Ignoring Cookies. The tracking cookies of Google (_ga and _gid) and Meta (_fbp) are the most common consent-violators. This highlights an important fact that users cannot opt out of tracking even when they explicitly reject the consent of such types of cookies. Table 8 shows the most common cookies with an Ignored Cookie Rejection violation.

Consent-Ignoring Trackers. We measured the number of 3rd-party cookies & trackers and the websites they were on. The most common cookie domains are found to be *doubleclick.net* and *youtube.com* which are tracking domains of the same owner *google.com*. Table 9 lists the top trackers.

Regional Discrepancies. The results of our crawls demonstrate a stark discrepancy in cookie count, cookie consent violations, and cookie banner implementations across different regions. These differences result in up to 3.44% more websites with undeclared cookies in some regions than the baseline EU and UK regions. The US contains 250,447, almost 3× more cookies than websites in the EU, and as much as 10% more undeclared cookies per website. A large number of websites also contain differences in cookie library implementations, with non-European regions containing more cookie banners that do not display "Reject All Cookies" buttons, have shorter consent lifetimes, and have opt-out or implied consent rather than opt-in banners.

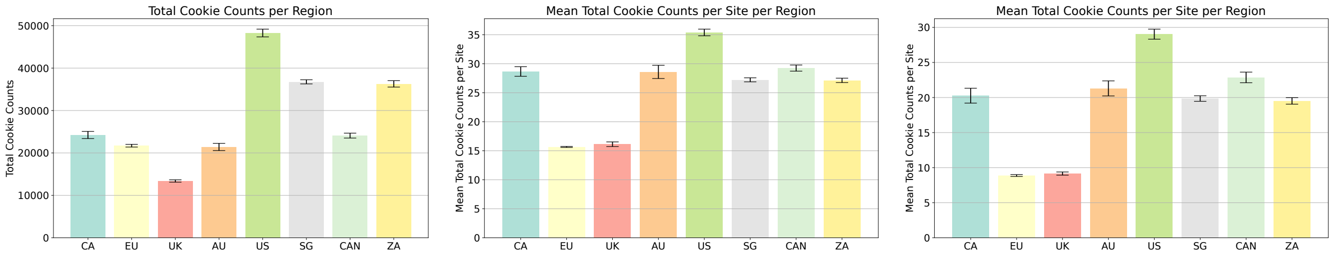
Personal Information. We analyze the contents of each cookie found in a cookie consent violation to determine whether they contain personal information, potentially violating user consent. The 75% of cookie consent violations likely involve cookies containing personal information. Table 7 contains statistics on cookies with tracking IDs (64.10%), location (7.44%), IP address (5.74%), and language (1%).

6.2 Major Findings

Finding 1: *The US has the most cookies, undeclared cookie violations, and ignored cookie rejection violations.* Even in CA, the state with the strictest privacy laws, the prevalence of undeclared cookies per site was found to be higher than the EU by 5.49%. The total undeclared cookie and ignored cookie rejection violation counts across 10 measurements in the US (MI) were 250,447 and 128,871 cookies, respectively.

Finding 2: *Cookies are much more prevalent in the non-GDPR regions.* European countries have the fewest 1st- and 3rd-party cookies placed on websites (EU has roughly 15.66 1st-party cookies per site and 8.88 3rd-party cookies per site, respectively). The US-MI has the most, with roughly 35.4 (1st-party) and 29.03 (3rd-party) cookies per site, followed by all other non-EU regions with between 27.14–29.26 1st-party cookies per site.

Finding 3: *3rd-party cookies still constitute a large number of cookie consent violations across regions.* While the EU and UK have significantly fewer 3rd-party cookies (Figure 4c), all other regions have a large number of 3rd-party cookies placed on each site. Third-party cookies in the US made up



(a) Total cookie counts (b) Mean cookie counts per website (c) Mean 3rd-party cookie counts per website

Figure 4: Cookie counts measured in our study.

Violation Type	California (CA)		Ireland (EU)		United Kingdom (UK)		Australia (AU)	
	# Cookies	% Websites	# Cookies	% Websites	# Cookies	% Websites	# Cookies	% Websites
Ignored Cookie Rejection	83,036	88.41%	72,928	86.09%	44,605	84.75%	60,985	80.74%
Undeclared Cookies	115,718	93.61%	87,251	90.19%	54,633	90.04%	99,893	92.86%
Wrong Cookie Category	316	3.03%	365	3.13%	206	2.82%	218	3.20%

Violation Type	Michigan (US)		Singapore (SG)		Canada (CAN)		South Africa (ZA)	
	# Cookies	% Websites	# Cookies	% Websites	# Cookies	% Websites	# Cookies	% Websites
Ignored Cookie Rejection	128,871	84.65%	107,233	82.22%	65,882	81.63%	107,072	81.97%
Undeclared Cookies	250,447	94.15%	167,979	92.90%	117,144	91.20%	165,647	93.56%
Wrong Cookie Category	300	2.50%	395	3.37%	272	3.35%	446	3.69%

Table 6: Total detected cookie violations across 10 repeated measurements.

roughly 29.03 cookies per site while websites in the EU and UK contained the fewest with an average of 8.88 and 9.16 cookies per site, respectively. These violations were found to be statistically significant (Section 5.4).

Finding 4*: Regions with fewer undeclared cookie consent violations have more ignored cookie rejection and wrong cookie category violations.* Figure 5a and fig. 5b show an inverse correlation between the number of ignored rejection violations and undeclared cookie consent violations. Most likely, website developers are more vigilant about categorizing undeclared cookies for GDPR compliance but neglect to update their non-GDPR CMP cookie lists. Consequently, sites in the EU and UK have higher rates of ignored cookie rejections likely due to an increase in declared cookies, but a lack of properly implemented CMP scripts. Undeclared cookies are placed regardless of rejection. These cookies are not even present in the cookie library and thus cannot be rejected.

Finding 5*: Cookie placement and violation rates can be categorized into three groups*: EU/UK (fewest cookies, highest compliance), CA, AU, SG, CAN, ZA (moderate cookie count and compliance), US (most cookies, lowest compliance). Without any privacy regulations, the US has poor cookie practices. In our analysis of websites' cookies and cookie consent violations, we ran pairwise comparisons on websites between different regions, discovering that all other regions, particularly the US, have a significant increase in cookie count and cookie consent violations compared to the EU and UK (Figures 8 and 9). These discrepancies were found to be statistically significant (Section 5.4).

Finding 6*: Cookie banners, their UIs, and their functionalities are different across regions.* Across the 8 studied regions, the cookie libraries and cookie banners have a significant number of differences in their configurations. The EU and US have the most pairwise disparities in cookie banner parameters. SG (5084), ZA (5097), and CA (4870) also contain a significant amount of cookie banner implementation differences to the EU, while Canada (3,050) and Australia (2,705) contain fewer differences. Websites in the EU and UK have more privacy-preserving configurations compared to other regions (consent models, reject all button appearance, etc.).

6.3 Contextualizing Findings with Prior Work

Although every measurement study uses different methodologies, we provide a comparison of broad trends to paint a picture of cookie consent compliance over time.

Increase in Overall Violation Rates. Early audits reported very high violation prevalence even on small samples. Sanchez-Rola (2019) *et al.* [56] found that 92% of 2k audited sites set tracking cookies before consent. Bollinger (2022) *et al.* [9] observed an increase of violations to 94.7% of 30k sites. Our crawl found at least one violation on 96.18–97.72% of sites — an absolute increase of 1–3% every three years. Though this increase may be due to many factors: website developers not updating CMPs and repeated measurements catching more violation instances, cookie consent violations appear to be increasing.

Undeclared Cookies. Bollinger *et al.* [9] reported 82.5% of sites deploying undeclared cookies in the EU. For other non-EU regions, we found that undeclared cookie violations were even more prevalent. Undeclared cookies remained the dominant category, with 90.19–94.15% of sites containing at least one undeclared cookie. These undeclared cookie violations are found to be more prevalent (3–4%) in non-EU regions than EU regions.

Implicit Consent and Ignored Rejections. Implicit consent —– often manifested as cookies being set despite explicit rejection —– has persisted and even grown more widespread. Bollinger (2022) *et al.* [9] report that 69.7% of sites commit implicit-consent violations and 21.3% ignore users' reject clicks, while Sanchez-Rola (2019) *et al.* [56] found 92% of 2,000 audited sites performed tracking before any consent. Bouhoula (2023) *et al.* [10] show 77.5% of EU sites implicitly consent when banners are closed. We found that "Ignored Cookie Rejections" affect 80.74% (Australia) up to 88.41% (California) of sites — with 44,605 ignored-rejection cookies in the UK and 128,871 in the US.

Geolocation-Specific Disparities. Rasaii *et al.* [54] reported banner prevalence of 47% in EU vs. 30% non-EU, and 83-–96% more tracking cookies outside the EU. Eijk *et al.* [28] measured a 102% increase in banner odds in the EU. We extend these findings by quantifying both violation counts and UI configurations: US sites average 46.5 first-party and 37.3 third-party cookies per site, approximately three times the EU's 20.0 and 11.0. Meanwhile, non-EU regions are 3.4% more likely to omit "Reject All" buttons and default to opt-out or implied consent models (32% of US sites).

6.4 Cookie Consent Violations Across Regions

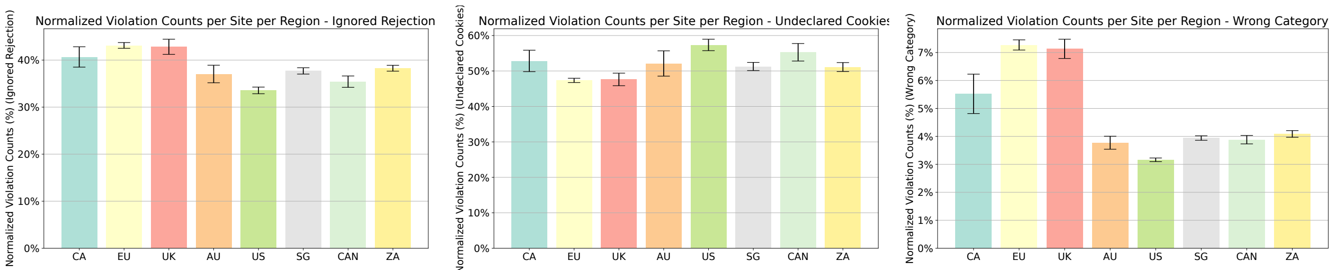
Overall, the EU and UK have fewer undeclared cookies (87,251 and 54,633), websites with undeclared cookies (90.19% and 90.04%), and undeclared cookie consent violations as a proportion of all cookies. Conversely, the number of ignored cookie rejection violations when normalized to the total cookie count is higher in these regions (Figure 5). Such a phenomenon can be explained by the increase in proper cookie declarations. For a cookie to be classified as an ignored cookie rejection by our system, it needs to be declared by the cookie library. Thus, the increase in declared cookies results in more cookies being continued to be placed even after the user rejects all cookies. In contrast, the US had the most websites with undeclared cookies with 95.93% of websites containing at least one undeclared cookie violation. AU had the third-fewest cookies loaded in our measurements. The region also had the fewest websites with ignored cookie rejection violations with only 80.74% containing these violations. CA had the most websites with at least one ignored cookie rejection, with 88.41%. Across all regions, wrong cookie category violations were found on very few websites, between only 2.50% and 3.69% of websites had one violation of this type. Despite Canada's PIPEDA having similar guidelines as the EU/UK regarding tracking cookie consent, this region contained more cookie consent violations. nhl.com contains cookies from googleadservices.com, an example of such an undeclared cookie violation (for tracking cookies in Canada). We found from our measurements that the same websites had many more cookies and cookie consent violations when accessed in different regions. Websites in non-EU/UK regions had roughly 8 additional cookies (Figure 8) and 7 additional cookie consent violations (Figure 9). As an example, nvidia.com had 16.25–24.00 cookies in AU, SG, EU, UK, CAN whereas it had 28.86–36.78 cookies in CA, ZA, US.

6.5 3rd-Party Cookies and Consent Violations

Third-party cookies were most prevalent in the US across websites by a large margin (29.03 cookies per site). Regions with websites containing the fewest set of third-party cookies with only an average of 8.88 (EU) and 9.16 (UK) cookies per site. Other regions like CAN (22.87), AU (21.3), CA (20.26), SG (19.86), and ZA (19.52) had fewer third-party cookies loaded per website, but still significantly more than websites accessed from the EU and UK. These discrepancies may be attributed to a combination of advertisers' interest in the regions' users and region-specific privacy laws. CMPs provide website developers with templates and location rulesets to customize cookie banners and cookie placement depending on the region. Advertisers may have a higher interest in CA users for these English-speaking sites than regions in Asia or Africa (so cookies are more prevalent). Combined with CA's stricter requirements on opt-outs, personal information, and cookie notices, website developers may declare more cookies for the CA region, but place fewer on these users' browsers. North American regions have the most undeclared cookies, with CA containing the fewest. Whereas AU, SG, and ZA contain more undeclared cookies than the EU and UK. An illustrative example of this is sportinglife.com which uses 3rd-party cookies from Google and DoubleClick. In CA, the website loads these undeclared cookies (e.g., NID, IDE) from both regions, whereas in the EU, the website does not load these cookies. Generally, the disparities observed in cookie consent violations (Figure 5) are exacerbated in 3rd-party cookie consent violations (Figure 6).

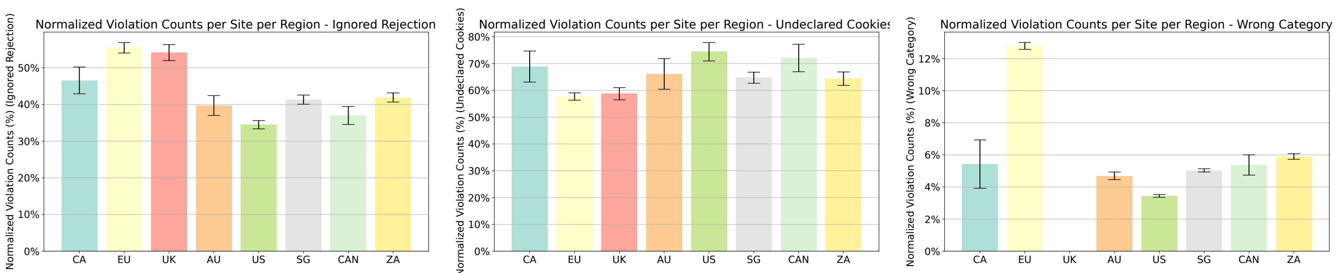
6.6 Cookie Banner and UI Discrepancies

We analyzed the OneTrust and Cookiebot cookie library configurations, both their consent choice and cookie banner UI



(a) Ignored Cookie Rejection (b) Undeclared Cookies (c) Wrong Cookie Category

Figure 5: Normalized average cookie violations per-website.



(a) Ignored Cookie Rejection (b) Undeclared Cookies (c) Wrong Cookie Category

Figure 6: Normalized average per-website 3rd-party cookie violations.

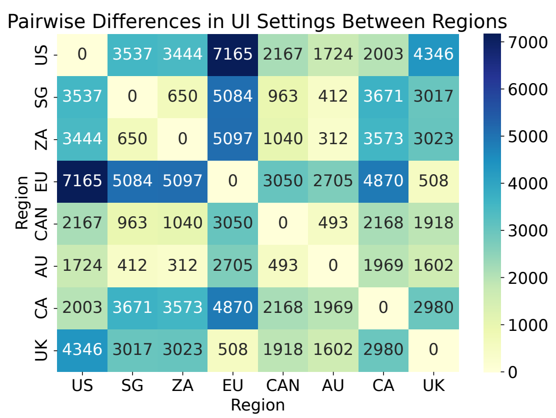


Figure 7: Pairwise website-level cookie banner implementation and UI differences across regions.

settings. These banners were found to change a significant number of parameters such as cookie banner text, button color and positioning, banner background color and positioning, cookie consent model (opt-in vs. opt-out, display banner vs. implied consent choice, etc.), cookie category names, cookie lifespan, consent choice lifespan, and more. The EU and US (Non-CA) have the most disparities in cookie banner implementations (7,165), likely due to the lack of any privacy regulations in Michigan. SG (5084), ZA (5097), and CA (4870) also contain a significant number of cookie banner implementation differences, while Canada (3,050) and Australia (2,705) contain fewer differences. Larger differences emerge between the US and CA compared to all other regions likely stem from its importance as a region for advertisers, whereas the EU and UK's discrepancies likely stem from their privacy regulations and cookie guidelines. SG, ZA, CAN, and AU all have few pairwise differences relative to each other, ranging from 312 to 1040, far fewer than the US, CA, UK, and EU.

Many of these differences are minor changes in the text or UI colors, nudging users to select certain choices. For example, sites that display an "ACCEPT ALL" button on their cookie banner are much more likely to be accessed from the EU and UK, whereas in the US, "OK" is more commonly used. Other differences completely change the consent model of the cookie banner (e.g., "opt-in" vs. "opt-out" or "1 month" vs "12 months" for consent duration). In regions like the EU and UK, the probability of seeing a "Reject All" button on the cookie banner is higher than in other regions. Regions like CAN and SG, despite having explicit guidelines on cookie consent for online behavioral advertising, have a smaller share of sites' cookie banners using "Reject All" buttons.

Figures. 7 and 10–16 show such differences in websites' cookie banner implementations. For example, Figures. 10, 12, and 13 all indicate that websites in the EU and UK tend to use more privacy-preserving practices and features, such as the consent choice lasting longer, giving users the option to reject all cookies, having both 1st-party and 3rd-party cookies be opt-in rather than opt-out or an implied consent choice.

7 Root Cause Analysis

We analyzed Onetrust and Cookiebot's documentation and demos to gain insight into whether CMPs or website developers hold responsibility for cookie consent violations. Although CMPs may act as data controllers or processors [58], both parties share responsibility. CMPs need to provide stronger guardrails, easier integration methods, support for more legal frameworks, and clearer documentation. Site owners need to ensure no undeclared cookies remain, properly implement cookie/script-blocking, and keep their CMP integrations updated. We find that most undeclared cookies result from either website developers not categorizing cookies or CMP crawlers missing some cookies, whereas ignored cookie rejections stem from developers not integrating CMP scripts correctly.

7.1 CMP Responsibility

Template Gaps: Most CMPs ship with templates only for major legal frameworks like GDPR and CCPA, leaving other jurisdictions unsupported. As a result, developers have no pre-configurations or guidelines for regions like Canada, Singapore, or South Africa, leading to inconsistent or noncompliant cookie banners (Figure 17). Note that these templates are useful for developers (unfamiliar with privacy laws) in determining cookie banner behaviors (e.g., whether they are shown, reconsent expiration time, etc. Figure 18).

Incomplete Automatic Crawling: CMPs commonly auto-detect 3rd-party scripts/iframes to populate banner catalogs and block rejected categories. However, content loaded only in specific contexts (e.g., embedded YouTube videos) can evade these crawlers, so cookies can slip through undetected, leading to undeclared cookie violations (Table 9).

Geolocation Rulesets: CMPs offer geolocation rulesets that dynamically adjust banner text, button labels, consent models (opt-in vs. implied), and even hide "Reject All" to maximize opt-in rates per region (Figure 19). CMPs support geolocation rulesets, which can allow for customizing cookie banner stylization and functionality depending on the region of the user's IP address. For example, the CCPA template for Onetrust supports translating behaviors like clicking or moving to the next page as the consent choice "Accept All Cookies" (Figure 18). At other locations without legal template support, website developers may set geolocation rulesets to not display cookie banners, or even allow scrolling to be counted as accepting all cookies. These rulesets account for the disparity in cookie placement and consent functionality between regions.

Dark Patterns and Opt-In Analytics: Cookiebot allows web developers to change cookie banner text and cookie banner stylization without guardrails. Developers can set arbitrary labels for buttons, for example, some sites used "Continue to Site" and "Close" as labels in place of "Accept All Cookies". Further, CMP dashboards provide A/B testing and opt-in analytics, incentivizing developers to create dark patterns and optimizing banner layouts for acceptance rate.

7.2 Developer Responsibility

Incorrect Script Embedding: In order for CMPs to block 3rd-party scripts that load cookies, website developers need to update any <script> tags with additional attributes (e.g., data-usercentrics="Google Maps" or <script class="optanon-category-C0002">). Additionally, CMP scripts connected to the Onetrust and Cookiebot services must be placed in the <head> *before* any other scripts [**cybot_automatic_2019** , 5, 20]. If these instructions are not followed perfectly, scripts will continue to load and cookies will be placed. Both OneTrust and Cookiebot's documentation states that if cookies or tracking scripts are loaded before consent withdrawal, then the developer or user needs to deactivate the service or perform a page reload [3, 19]. A manual inspection revealed that websites left scripts uncontrolled by the CMPs. For example, on *scientificamerican.com*, we rejected *Performance cookies*, but found that both first- and third-party Analytics cookies such as Google Analytics (*_ga*) were still being loaded (Table 8).

Manual Cookie Categorization: When CMP auto-scanners miss new or previously uncategorized cookies, developers need to manually assign them to categories. In practice, these manual steps could be easily missed or skipped, so these "unknown" cookies remain undeclared and active. These missed cookies likely make up the bulk of the undeclared cookie violations (Figure 16).

Neglecting Updates: Websites frequently change [2], and web developers may forget to have CMPs re-crawl their sites and update their scripts, especially on new subdomains. The Cookiebot scanner is also priced to scale with the number of subpages to crawl, and thus may provide incomplete scans. These may also contribute to undeclared cookies.

Banner Localization Oversights: Beyond CMP geolocation tweaks, developers may hardcode or override banner text, styling, and behaviors for each locale.

8 Conclusion

We presented `ConsentChk`, an automated system that detects cookie consent violations on websites across the world. We also developed a formal model to systematically analyze the (in)consistencies between users' cookie consent preferences and actual cookie usage of websites. Our findings indicate that the majority of the studied websites contain inconsistent and potentially non-compliant cookie consent behavior in the measurements from 8 regions. Our findings suggest the existence of systemic issues with cookie banners and CMPs, highlighting the need for larger-scale auditing and enforcement of cookie usage to protect users' autonomy and privacy.

9 Ethics Considerations

Our study was conducted with strict adherence to ethical research practices, ensuring minimal impact on the websites and their users. All data was obtained from publicly accessible websites via browser automation tools (e.g., Playwright, Puppeteer). We crawled the sites and performed our measurements without storing their HTML or page data. The study focused solely on analyzing CMP libraries and cookie data.

To conduct a comprehensive analysis across regions, we utilized AWS and DigitalOcean proxies to access websites from different geographic locations. Basic bot detection evasion techniques were employed to increase coverage. Our crawling processes were designed to generate minimal traffic, only repeating the measurements 10 times to ensure reproducibility. We avoided straining servers and disrupting normal website operations by spacing the measurements over a week.

10 Compliance with Open Science Policy

To uphold principles of transparency and reproducibility, the source code of our crawling and measurement system, alongside the analysis scripts and cookie data are available at https://github.com/byron123t/cookie-consent.

However, certain components of our system are subject to patents and institutional licensing restrictions, which may prevent full functionality of the shared code. We will make the code functional without these components, with this code being available upon request and approval by our institution.

11 Acknowledgements

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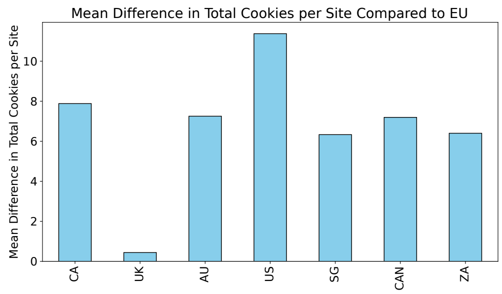

Figure 8: Relative website-level differences in total cookies. (Compared to EU baseline)

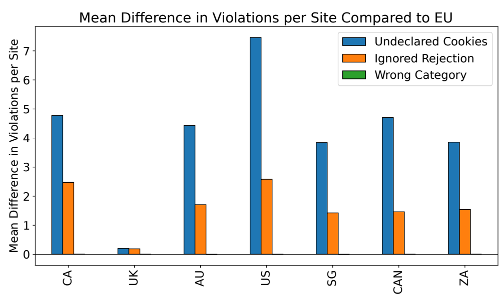

Figure 9: Relative website-level differences in cookie violations. (Compared to EU baseline)

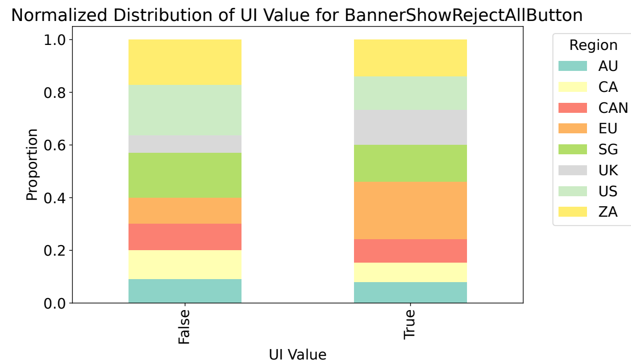

Figure 10: Reject all button presence in cookie banners.

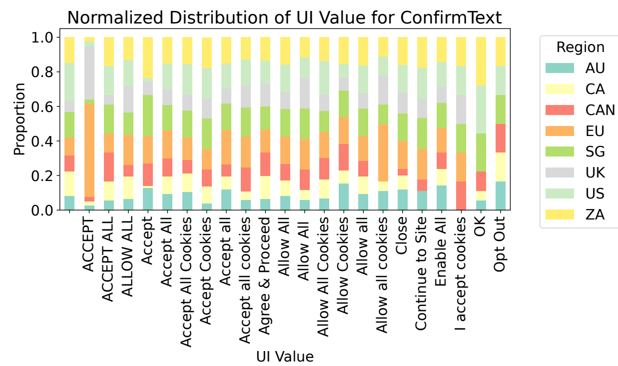

Figure 11: Pairwise website-website cookie count differences.

A Preference Button Extractor

A.1 Button Extractor Data Collection

We randomly selected 8k websites from the top 10k global websites for developing features and training the button extractor. The remaining 2k websites were set aside to evaluate the model performance. We use the Tranco list [42] generated in July 2021 (ID: 9QK2) and accessed websites from an IP address in the UK to maximize encounters with cookie banners and preference buttons. We manually visited the home pages of 1,000 randomly selected websites from the 8k websites to identify cookie banner buttons. Two annotators independently annotated the home pages of the websites. For each website, a snapshot of the home page HTML and the CSS selectors were recorded. Only the websites with English home pages were annotated, excluding non-English pages and duplicates. We obtained a training set of 298 web pages containing 436 cookie banner buttons out of 71,020 all links/buttons. Many websites only show a cookie banner without any choice or only a binary accept/reject option.

A.2 Button Extractor Feature Selection

We derive 3 classification feature groups based on the HTML attributes: aria-label, class, id, and inner text. The attribute *aria-label*, an accessibility feature of the web for marking buttons with labels for users with disabilities [17], is especially useful in cases where buttons are displayed as non-textual icons. The features are shown in Table 10 and the feature vector has 17 dimensions in total. Feature group G_1 is the number of occurrences of selected unigrams, bigrams and high-frequency keywords in the button labels. We also separate the most frequently-used bigrams into a set of high-frequency keywords (Table 11 lists some examples). Feature group G_2 indicates whether or not the number of tokens of a button label is greater than a threshold $n_t = 9$ (empircally selected using training set). This feature allows our classifier to avoid long paragraphs that may contain keywords. Finally, feature group G_3 indicates whether a cookie consent library API is being used.

A.3 Button Extractor Performance Metric

We report the *recall@k* score, a metric used to evaluate information retrieval systems [34, 61, 66], which represents the portion of websites containing cookie banner buttons detected from the top *k* classification results. A website is successfully detected if one of its cookie banner buttons is among the top *k* buttons with the highest classification probabilities.

% Cookies	CA	EU	UK	AU	US	SG	CAN	ZA
Trackers	63.87%	64.10%	64.14%	63.36%	64.73%	62.89%	64.11%	64.40%
Location	7.34%	7.44%	7.38%	7.93%	8.18%	7.99%	8.19%	7.46%
IP Address	3.28%	5.74%	5.58%	3.51%	2.81%	3.54%	3.01%	3.81%
Language	0.54%	1.00%	0.92%	0.52%	0.45%	0.55%	0.51%	0.57%
Unlikely P.I.	24.98%	21.98%	21.30%	23.84%	25.03%	25.50%	24.09%	24.76%

Table 7: Violations and cookies containing personal information in the form of trackers, ip, or location data.

Cookie Name	# Websites (%)
_ga	583 (48.4)
_gid	429 (35.6)
_fbp	318 (26.4)
IDE	296 (24.6)
_uetsid	218 (18.1)

Table 8: Top-5 Rejected Cookies Used.

Tracker	# Websites (%)
doubleclick.net	328 (27.2)
linkedin.com	198 (16.4)
youtube.com	198 (16.4)
bing.com	88 (7.3)
twitter.com	69 (5.7)

Table 9: Top trackers of rejected-usage cookies.

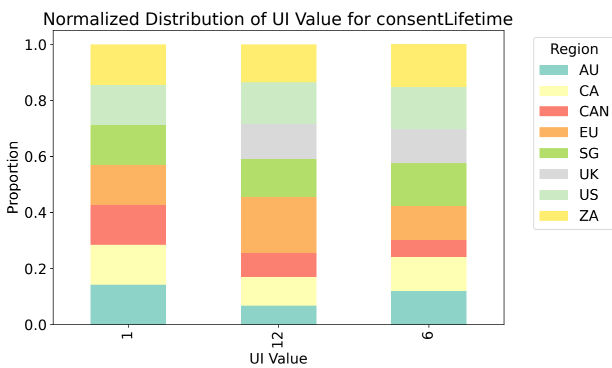

Figure 12: Pairwise cookie consent lifetime differences.

A.4 Button Extractor Model Selection

After evaluating various ML algorithms including regression, perceptrons, SVMs, etc., we find that the best-performing classifier is a random forest (RF) with 100 decision trees which achieves the best *recall@1* score of 80.22% ($1 \leq k \leq 10$, 10-fold cross-validation). It consistently outperformed other models *recall@k* for $k \in \{1,3,5,10\}$. Fig. 15 shows the *recall@k* scores of the models. Using 57 websites containing preference buttons from the 2k domains in the test set, we find that the performance of the model achieves *recall@1*, *recall@3*, *recall@5* and *recall@10* scores of 77.19%, 85.96%, 85.96%, and 89.47%. These are the recall scores for the top 3, 5, and 10 detected objects.

B Consent Cookie Decoding

To extract cookie consent preferences, we decode consent cookies basing on the documentation and analyzing their key-value pairs. OneTrust's consent cookie is called *Optanon-Consent* [49] which stores the consent preference of each cookie category. For example, *groups=C1:1,C2:0* indicates that cookie category *C*1 is approved while *C*2 is rejected. Cookiebot's consent cookie is called *CookieConsent* storing consents for 4 fixed cookie categories: Necessary, Preferences, Statistics, and Marketing [23]. Similar to 'Necessary' cookies, 'Unclassified' cookies are not automatically blocked and cannot be denied by users, so the consent preferences for these cookies are by default set to True [22].

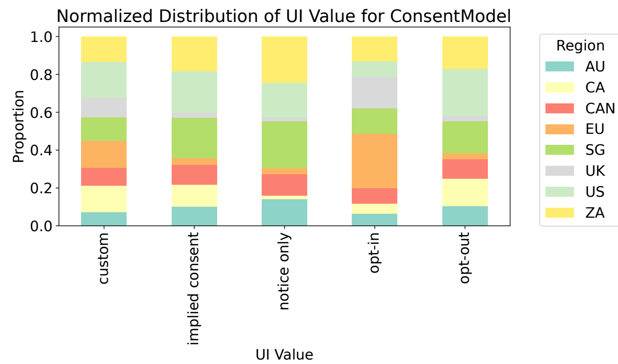

Figure 13: Pairwise CMP behavior differences.

Group	Examples
Unigrams	adchoice, adjust, change, choice, choose, configure, consent, cookie, customise, customize, manage, option, personal, preference, privacy, review, setting, update, view
Bigrams	configure consent, set preference, advanced setting, privacy setting, update preference, personal information, manage preference, california sell, privacy preference, sell personal, consent detail, manage setting, change privacy, view cookie
Keywords	change consent, change setting, consent choice, consent tool, cookie consent, cookie preference, cookie setting, customize setting, manage cookie, review cookie

Table 11: Examples of n-grams and high-frequency keywords extracted from the button labels.

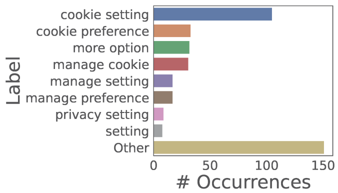

Figure 14: Distribution of labels of cookie banner buttons.

G	Feature (Dimension)	HTML attributes	D_G
G_1	# n-grams and keywords (3)	aria-label, class, id, text	12
G_2	# tokens $> n_t$ or not (1)	aria-label, text	2
G_3	Has consent library API (1)	class, href, id, onclick	3
		Total	17

Table 10: Cookie button detection features. G and D_G stand for a feature group and its dimension.

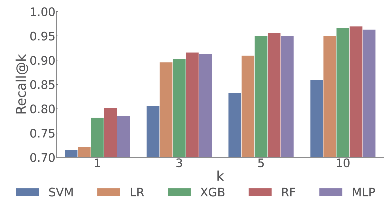

Figure 15: Top-k scores of 10-fold validation of ML models.

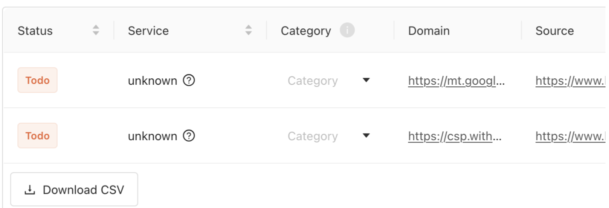

Figure 16: Cookiebot developer interface for handling uncategorized and undeclared cookies.

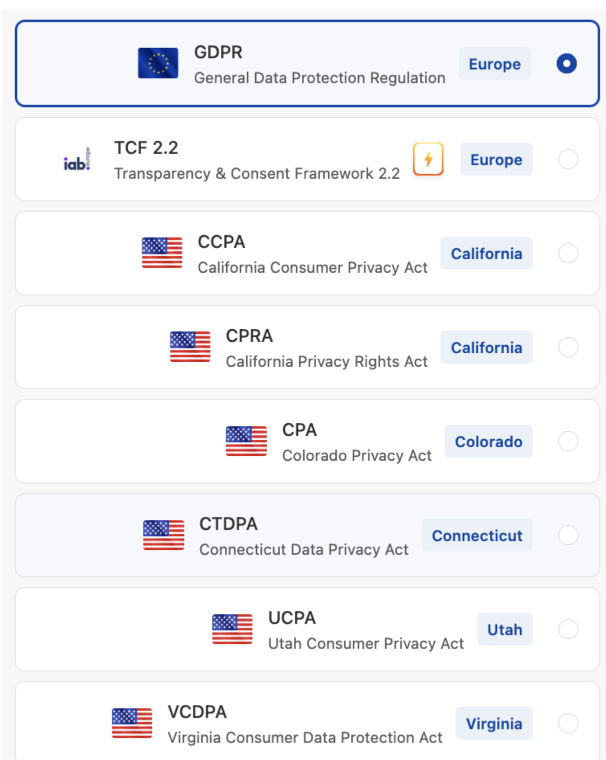

Figure 17: Cookiebot options for regional privacy law templates and cookie banner implementation guidelines. Missing: Singapore, Canada, Brazil, South Africa, etc.

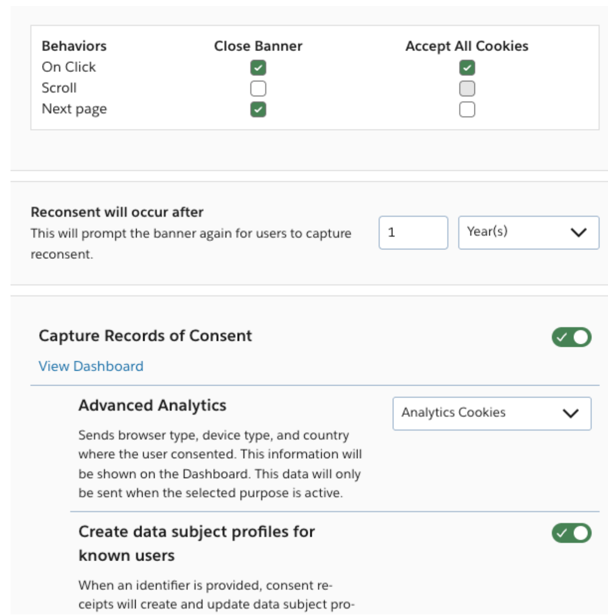

Figure 18: Onetrust developer interface for consent expiration and automatically setting consent on user behaviors.

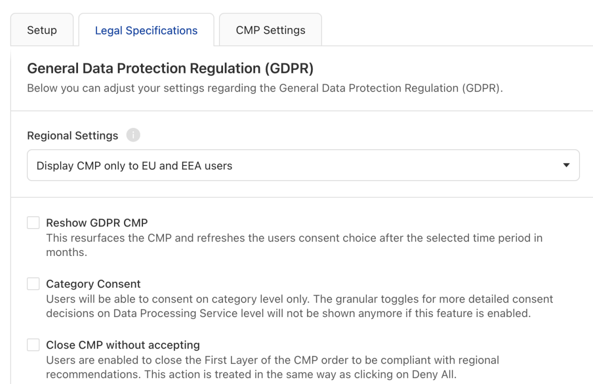

Figure 19: Cookiebot geolocation rulesets and default options for CMP display.