COMPULSORY LICENSING - DID PATENT VIOLATIONS DURING THE GREAT WAR DISCOURAGE INVENTION?*

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This paper examines whether the US decision during World War I to violate enemy-owned patents - through compulsory licensing - discouraged invention. Estimates from a new data set of German patents indicate a 28 percent increase in invention. Controls for patent quality suggest that only a small share of the increase was due to lower quality, strategic patents. Firm-level data suggest that compulsory licensing facilitated competitive entry into fields with licensing. Firms whose patents had been licensed began to patent more in research fields with licensing. The increase in patenting was strongest for fields with low levels of pre-existing competition.

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Whether policies that strengthen intellectual property rights encourage or discourage innovation is a subject of intense debate. Basic models of intellectual property indicate that policies, which weaken intellectual property, will discourage innovation by reducing the ability of inventors to recoup costly investments in R&D (Scotchmer 2004, pp. 35-36).[1] Economic models of competition and innovation, however, predict that increasing competition can encourage innovation (Arrow 1962a; Aghion et al. 2001, 2005),[2] and policies that limit the strength of patents, such as compulsory licensing, can increase competition by allowing a new set of firms to produce a patented technology.

Compulsory licensing is an intellectual property policy that allows government agencies to issue licenses for patented technology *without the consent of patent owners.* Although compulsory licensing is a clear violation of intellectual property, Article 31 of the Trade-Related Aspects of Intellectual Property Rights Agreement (TRIPS) permits it in emergencies of public safety and health. In recent years India, Brazil, and Thailand have invoked such emergencies to improve access to drugs to combat HIV and other life-threatening diseases. Critics, however, caution that "pharmaceutical companies face the risk of receiving only a drastically reduced royalty for the use of their intellectual property, imperiling in turn their ability to develop profitably new treatments and molecules."[3]

This paper exploits the US decision in 1918 to make all patents by war enemies available for compulsory licensing to investigate the potential effects of this policy on innovation. Intended to "destroy Germany's great industrial army on

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[1] An increasing amount of empirical evidence suggests that the benefits of stronger intellectual property rights can be moderate. Sakakibara and Branstetter (2001) find that an expansion in the scope of patents led to a modest increase in R&D and patenting in Japan. Nineteenth-century exhibition data, as an alternative measure (non-patent) measure of innovation, indicate that the existence of an effective patent system may influence the *direction* if not the level of technical change (Moser 2005). An analysis of scientific advances surrounding the human genome shows that even short-term intellectual property rights can discourage innovation (Williams 2013).

[2] See Gilbert (2006) for a survey of the "seemingly endless variations in the theoretical relationship between competition and expenditures on research and developments or the outputs of research and development" (R&D), as well as earlier waves of empirical research on competition and innovation.

[3] *thepharmaletter*, March 21, 2014.

American soil," the US Trading-with-the-Enemy Act (TWEA) allowed US agencies to appropriate all German-owned property in the United States, including all German-owned patents.[4] From 1919 to 1926 the US Chemical Foundation granted 693 non-exclusive compulsory licenses of German-owned US patents "upon equal terms and a royalty basis, to any bona fide American individual or corporation" (Haynes 1945, p. 260). Previous research on the effects of this Act has revealed a substantial increase in innovation in the United States, as the country that benefitted from access to German-owned patents (Moser and Voena 2012). The welfare effects of compulsory licensing, however, critically depend on its effects on inventors whose patents are violated.

This paper examines a new data set of German patents for chemical inventions to investigate the effects of compulsory licensing on German inventors. Our analysis focuses on chemicals and pharmaceuticals because these technologies are important targets for compulsory licensing today. Moreover, patents are considered an effective mechanism to protect intellectual property in chemicals and pharmaceuticals, which suggests that patent data are a useful proxy for innovation. Our data cover all 79,591 granted patents for German patents across 212 subclasses in the classification system of the German Patent Office (GPO) with application years between 1900 and 1930. To match research fields that were affected by compulsory licensing in the United States with research fields in Germany, we create a new concordance that matches subclasses in the United States patent system (USPTO) with subclasses in the German patent system. A total of 1,246 US patents by German firms became subject to compulsory licensing under the WWI TWEA; these patents cover 101 of 212 GPO subclasses. To investigate changes in invention at the level of individual firms, we also match patents with German firms. 4,814 firms applied for at least one chemical patent in Germany between 1900 and 1930; 50 of these 4,814 firms owned at least one US patent that was licensed.

[4] Alien Property Custodian 1919, p. 14. The TWEA was enacted on October 7, 1917 as 40 Stat. 411, codified at 12 U.S.C. § 95a et seq.

Baseline specifications compare changes in patents per subclass and application year after 1918 in subclasses with and without licensed patents. This difference-in-differences approach allows us to examine the effects of compulsory licensing, controlling for unobservable factors, such as reparations and punitive tariffs, which may have influenced invention. Control variables for German patents by US and other foreign inventors proxy for other factors that may have caused patenting to vary across technologies and over time.

This analysis reveals an *increase* in German patents after 1918 for subclasses in which German patents were licensed to US firms. On average, German inventors applied for 2.97 additional patents per year after 1918 in subclasses with licensing. Compared with an average of 10.77 patents per year until 1918 for subclasses with licensing, this implies a 28 percent increase in patenting for subclasses with licensing.

An empirical challenge for our estimation approach is that US firms may have been more likely to license German-owned US patents in fields in which the demand for improvements increased after 1918. Then, the observed increase in patenting may reflect selection into research fields with licensing rather than an effect of compulsory licensing. Historical records, however, suggest that fields in which demand had been high during the war, such as dyestuffs and explosives, faced severe problems of excess capacity after 1919 (Haber 1971, p. 251). Then OLS estimates may underestimate the true effects of licensing. To address this issue, we estimate intent-to-treat and instrumental variable regressions with subclasses with confiscated patents as an instrument for subclasses with licensing. These estimates indicate that OLS estimates are downward biased.

Intuitively, compulsory licensing may lead to an increase in patenting by encouraging inventors to apply for a new set of patents on the same inventions or by encouraging them to invest in R&D. Analyses with renewal data as a control for patent quality (Schankerman and Pakes 1986) suggest that some of the observed increase in patenting may have been strategic; they do however also indicate that the observed increase in patenting cannot be explained by low-quality, strategic patents. Baseline estimates with renewed patents as an indicator for high-quality patents indicates a 17 percent increase in patenting.

To investigate the potential mechanisms by which compulsory licensing may have encouraged innovation, we perform a firm-level analysis of changes in patenting. This analysis reveals a significant increase in patenting after 1918 for German firms whose patents had been licensed. Baseline estimates indicate that firms whose patents had been licensed applied for 0.42 additional patents per subclass and year in subclasses with licensing compared with other German firms. Relative to an average of 0.46 patents per subclass and year until 1918 for firms with licensed patents, this implies a 91 percent increase.

Firm-level analyses also indicate a substantial increase in the number of firms that were active patentees in research fields with licensing. A comparison of changes in patenting for subclasses with low and high levels of competition confirms the first half of the inverted U shaped relationship between competition and innovation predicted by Aghion et al (2001; 2005), but shows weaker support for the second part of the inverted U. These results suggest that compulsory licensing can promote innovation by increasing competition in research fields with licensing, which tend to be relatively concentrated.

I. THEORETICAL PREDICTIONS

This section discusses the theoretical predictions that motivate the empirical analysis in this paper. These predictions are derived primarily from theoretical models of the effects of competition on innovation. By allowing a new set of firms to produce a patented invention, compulsory licensing increases entry (or the threat of entry), which increases competition. Whether or not competition encourages innovation is theoretically ambiguous.

A. More Competition Can Discourage Innovation

Theories that predict a negative link between competition and innovation can be traced back to Schumpeter (1934 and 1942), who argues that large firms and a relatively concentrated market structure can promote innovation by improving the ability of innovators to capture the returns from R&D. Goettler and Gordon (2011) confirm these predictions with estimates of a dynamic oligopoly model for the durable goods microprocessor industry; their estimates imply that the rate of innovation in product quality would be 4.2 percent higher if IBM was a monopolist.

In the context of intellectual property, Schumpeter's hypothesis implies that patents can encourage innovation by granting temporary monopoly rights to inventors, which enable them to recover costly investments in R&D (Scotchmer 2004, pp. 36-39). This suggests that compulsory licensing can discourage innovation by weakening the effectiveness of intellectual property and by reducing inventors' ability to recover investments in R&D.

B. More Competition Can Encourage Innovation

There are, however, many circumstances for which economic theory predicts a positive link between competition and innovation. Arrow (1962a), for example, shows that, if patents create exclusive monopoly rights to inventions, incentives to innovate are smaller for a monopolist who faces no (actual or potential) competition, compared with a competitive firm. For the monopolist, the stream of rents from an innovation replaces an existing stream of rents. For a competitive firm, there are no existing streams of rents, so that incentives to innovate are higher for the competitive firm than for the monopolist.[5]

[5] A patent race model, in which the firm that invests most in R&D wins the race with certainty, implies that a monopolist can have stronger incentives to invest in R&D because the monopolist is motivated to *preempt* competitive entry (Gilbert and Newberry 1982). Reinganum (1983), however, shows that Arrow's "replacement effect" prevails if the innovation is drastic and invention follows a (uncertain) discovery process that is exponentially distributed.

Consistent with these predictions, Acs and Audretsch's (1988) have documented a positive correlation between industries with lower levels of concentration and innovation, using data on 8,074 US manufacturing innovations listed in 1982 trade journals. Nickell (1996) similarly finds a positive correlation between the numbers of firms and total factor productivity growth for 670 UK manufacturing firms between 1972 and 1986. Blundell et al. (1999) show that industries with lower levels of concentration produced more "technologically significant and commercially important" innovations, using data for 340 manufacturing firms listed on the London Stock Exchange between 1972 and 1982.

An extension of models of cumulative invention (Scotchmer 1991) to compulsory licensing also suggests that compulsory licensing can encourage innovation. By reducing the strength of intellectual property rights of an early generation of inventors, compulsory licensing can increase the expected returns from follow-on (cumulative) innovation. Compulsory licensing may also encourage innovation by creating new opportunities for learning-by-doing (Arrow 1962b), as a new set of firms is allowed to produce a patented invention. Consistent with this hypothesis, Moser and Voena (2012, pp. 421-23) document a differential increase in US patents by the US chemical firm DuPont for fields in which DuPont licensed German patents under the TWEA.

C. Inverted U

Aghion et al. (2001 and 2005) reconcile predictions about the effects of competition on innovation to predict an inverted U-shaped relationship between competition and innovation.[6] At low levels of competition, a shift towards competition can encourage innovation by encouraging incumbents to invest in R&D

[6] Schmidt (1997) predicts an inverted U by incorporating bankruptcy: Competition increases the risk of bankruptcy, which encourages managers to innovate to preserve their jobs, but also reduces returns from cost-saving innovations by reducing demand for each firm. At high levels of competition, the latter effect dominates so that investments in R&D peak at an intermediate level of competition.

to "escape" competition. At high pre-existing levels of competition an additional increase in ("neck-and-neck") competition discourages innovation by further reducing post-innovation rents. These predictions are confirmed in a data set of UK patents issued to 311 firms between 1973 and 1994. Patenting increases in response to shifts towards competition at low levels of competition, but declines when pre-existing levels of competition are high (Aghion et al. 2005).

In the context of intellectual property rights, predictions of an inverted U imply that compulsory licensing can promote innovation in concentrated industries, and discourage innovation in industries that are already fairly competitive.

II. DATA

To investigate whether compulsory licensing encouraged or discouraged invention, we have constructed a new data set on 79,591 German patents for chemical processes and products.[7] Our data start with patent applications in 1900, the first year in which the GPO systematically assigned all patents to technology fields (GPO subclasses).[8] We collect patent applications until 1930; all of these applications had been issued by 1932, the last year before the Nazi government introduced discriminatory labor laws and began to dismiss Jewish scientists.[9] Our data expand on aggregate-level data on German patents (for example, Richter and Streb 2011) by including the identity of all inventors, their countries of residence, firm-level identifiers, and information on renewal payments for all patents. The data

[7] An 1891 reform of the German patent system had introduced product patents for chemicals; until then Germany had only granted patents for chemical processes (Haber 1971, p. 218).
[8] Until 1900, patents were assigned to 89 numerical (main) classes; in 1900 the German Patent Office expanded this classification to create 513 alphanumeric subclasses.
[9] The April 7, 1933 *Law for the Restoration of Public Service* dismissed all professors with a Jewish grandparent from public service. Analyses of US patents indicate that German-Jewish émigrés created substantial benefits for US invention (Moser, Voena, and Waldinger, forthcoming).

cover 212 GPO subclasses, including 101 subclasses in which at least one German-owned patent was licensed under the TWEA.[10]

A. Confiscated and Licensed US Patents

US authorities confiscated a total of 4,706 German-owned US patents under the TWEA; 1,246 of these patents were licensed to US firms. On December 12, 1918, US authorities auctioned off 551 US patents by the German Bayer AG to the US Sterling Company (Alien Property Custodian 1919, p. 440-53). Sterling sold Bayer's dye business to Grasselli Chemical and used Bayer's dye patents to produce pharmaceuticals through its division, Winthrop Chemical.[11] Beginning in 1919, the US Chemical Foundation licensed another 695 German-owned US patents to US firms. These licenses were issued "with low royalty payments, to facilitate broad-based access to German-owned patents " (Haynes 1945, p. 260). Licenses through the Chemical Foundation were non-exclusive; the average German-owned US patent was licensed to 2.5 firms, but the median patent was licensed to a single firm.[12] The exact timing of the licenses is unknown; Steen (2001), however, observes that most licenses were issued between 1919 and 1922.

Among 1,246 licensed patents listed in Haynes (1945) and the report of the Alien Property Custodian (1919), 1,017 patents include the name of the German firm who owned the licensed patent. Another 229 licensed patents list the US Chemical

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[10] Based on the classification of patents in the *Systematische Übersicht der vom 1. Januar bis 31. Dezember 1912 in die Patentrolle eingetragenen Patente* (1912).

[11] Alien Property Custodian 1919, p. 439 and Appendix 6 schedule 2; Hounshell and Smith 1988, p. 92. Critics of the auction argued that the Custodian had destroyed the German dye cartel merely "to build an American dye trust," and demanded the creation of an independent organization to distribute patents more broadly (Haynes 1945); this criticism led to the creation of the Chemical Foundation.

[12] Haynes reports the identity of the US licensees for 587 of 695 patents licensed by the US Chemical Foundation. Two patents by Krupp's metallurgist Benno Strauss (1873-1844) for stainless steel (1,316,817, "Articles which require high resistance against corrosion" and 1,339,378 "Objects having great strength and great resistance against the action of acids") were each licensed to 91 US firms. Both patents are in the USPTO subclass class 420/34 and German patent class 40b "alloys." Patent data, which we describe below, indicate that German patents for alloys nearly tripled after 1918 (from 4.95 patents per year to 16.92).

Foundation as an assignee. The remaining 208 patents belong to individual inventors. Fifty-three are patents by co-inventors of a German firm. For example, Dr. Richard Herz from Frankfurt is listed as an inventor for US patents 956348, 960919, and 966092 of the German firm Cassella, and we assign one remaining US patent by Dr. Herz (US patent 1243171) to the same firm.

B. German Patents 1900 and 1930

To examine changes in invention, we collected information on all patents issued in Germany between 1900 and 1932 across 212 subclasses of chemical inventions. To digitize these data, we first trained a group of typists to read German *Fraktur* with 99 percent accuracy, at less than one misspelled letter per page. They then collected the complete records of patent issues for chemicals from the Annual Reports of the German Patent Office (*Kaiserliches Patentamt,* 1900-1932). We then checked all entries to correct typographical errors in the description of inventions, inventors' names and cities. By this process we were able to collect information on 79,591 German patents issued for chemical processes and products between 1900 and 1932. These patents have application years between 1900 and 1930.

C. Technology Concordance across US and German Patents

To identify research fields in which German inventors were affected by compulsory licensing, we created a new concordance between subclasses in the US and German system. First, we used an existing USPTO concordance to match all 7,699 USPTO subclasses classes with 7,010 subclasses in the International Patent Classification (IPC).[13] We then match IPC subclasses with all 513 subclasses in German patent system, using a corresponding classification by the German Patent Office (Appendix Table A1 and Figure A1). The USPTO, however, cautions that its USPTO-IPC concordance "should be treated merely as suggestive of classification

[13] USPTO Office of Classification Support, Reference Tools Project. Available at http://www.uspto.gov/web/patents/classification/international/ipc/ipc8/ipc_concordance/ipcsel.htm.

places in the two systems that may be similar," and warns that not all US and German subclasses can be matched with an IPC subclass.

To improve on the USPTO-IPC-GPO concordance, we exploit a reporting requirement as a result of the 1883 Paris Convention to identify US and German patents that were granted *for the same invention*. The Paris Convention's *Right of Priority* allows inventors to apply for patents in other member countries within 12 months of the original application.[14] Germany ratified the Paris Convention in 1903, allowing inventors to apply for patents in Germany within 12 months of an application for the same invention in the United States. We exploit this rule to augment the USPTO-IPC-GPO concordance with information on subclasses that cover the same invention in the US and German system. Specifically, we search for references to US patent applications among the 71,770 German patents with application years after 1903.[15] This search yields 1,343 pairs of German and US patents for the same invention, which we use to identify subclasses that cover the same invention in the US and in the German patent systems. With this additional information, we are able to match 3,533 licensed US patents with 167 subclasses in the GPO's classification system (Appendix Table A1).[16]

Among 212 GPO subclasses, the average subclass includes 8.59 licensed and 19.51 confiscated patents (Appendix Table A2). The average GPO subclasses with at least one licensed patent includes 18 licensed and 57.56 confiscated patents (with a standard deviation of 53.65 and 64.33, respectively). Four subclasses include more

[14] *International Convention for the Protection of Industrial Property* 1883, Articles 4A and 4B. TRIPS requires all WTO members to comply with Article 4 of the Paris Convention.

[15] We first performed an automated search to match German with US patents (http://patft.uspto.gov/, accessed October 2012), using the title of the invention, the name of the inventor, and the application date. We hand-checked a random 10 percent sample of 46 patents; in this sample, 45 patents can be uniquely matched. 23 of 1,343 German patents with US application dates are for chemicals; 505 are by US nationals, 69 are by Germans, and 49 by nationals from 8 other countries.

[16] Using both information on primary and secondary (cross-references) subclasses of licensed German-owned US patents. Each US patent is assigned to one single primary subclass and may be assigned to one or more additional cross-reference subclasses, which patent examiners use to identify related technology fields. See Lampe and Moser (2014) for a detailed discussion.

than 100 licensed patents: 22a *azo dyes* (436 licensed patents), 12o *hydrocarbons* (242), 12i *metalloids (*146), 12q *aminophenol* (110), and 12k *ammonia* (108).

D. Inventors' Countries of Residence

To separate patents by German and foreign inventors, we extract text strings with information on inventors' city of origin from each patent and use city data to assign inventors to countries of origin. Among a total of 79,591 German patents, 58,691 are by German inventors; 20,900 patents by foreign inventors, include 4,133 patents by inventors from the United States, 3,162 from Great Britain, 3,041 from France, 2,984 from Switzerland, and 1,458 from Austria.[17]

We use data on German patents by US inventors to test whether US inventors began to patent more in subclasses with licensing. OLS estimates in Moser and Voena (2012) imply a 20 percent increase in US patenting by domestic US firms in subclasses, in which at least one German-owned patent was licensed (Moser and Voena 2012, pp. 404-5). Our data on German patents confirm that US inventors began to patent substantially more in subclasses with licensing after 1918 (Figure 2). Between 1900 and 1918, US firms applied for 0.67 German patents per subclass and year in subclasses with licensing, compared with 0.56 patents in other subclasses of chemical inventions. After 1918, US firms applied for 0.91 additional German patents per year in subclasses with licensing compared with 0.37 German patents in other subclasses.

E. Renewed Patents to Proxy High-Quality Patents

Griliches (1990, p. 1669) observed that patents "differ greatly in 'quality,' in the magnitude of inventive output associated with them." To measure such

[17] A small number of Austrian-owned US patents, 32 patents, were subject to compulsory licensing under the TWEA. To estimate the effects of compulsory licensing as conservatively as possible, we exclude these patents from the treatment variable, and assign German patents by Austrian inventors to the control variable *patents by other foreign* inventors.

variation, Schankerman and Pakes (1986) propose to use inventors' decisions to pay substantial renewal fees as a measure for the private value of a patent. Harhoff et al. (1999) document a positive correlation between inventors' reported valuation of patents and the number of years for which inventors renewed their patents. Lanjouw et al. (1998), however, caution that researchers cannot observe the true valuation of patents that are renewed for the full term, if renewal fees are low.[18]

In Germany, renewal fees were high, and renewals became more and more costly as the patent aged (Appendix Figure A2), so that renewal decisions were economically meaningful. In the first two years, renewal fees were 50$\mathcal{M}$ per year; this is equivalent to $243 in 2012 using purchasing power (as the most conservative conversion) and $1,340 using income value (which yields the largest estimate, Williamson 2014).[19] After the second year, renewal fees increased by 50$\mathcal{M}$ each year, reaching 700$\mathcal{M}$ in the 15th year, which was the end of the statutory term. Patents that were renewed for 5 years or more required inventors to pay a minimum of 550$\mathcal{M}$ in renewal fees, between $2,670 and $14,700 in 2012. By comparison, US renewal fees were only $1,600 in 2012 and 2014, due 3.5 years after the issue date.[20]

To construct renewal data, we followed all 79,591 GPO patents for chemicals through renewal records in the Annual Reports of the German Patent Office between 1901 and 1942. Half of all patents - 39,682 (49.86 percent) - were renewed for 5 years or more; we use these patents as a proxy for high-value patents.[21] More

[18] Patent citations, as an alternative measure of patent quality, are not available for German patents because references to prior art were not recorded on the patent document. Trajtenberg (1990) shows that counts of citation are correlated with the social value of patented invention proxied by the estimated social surplus of 456 improvements in CT scanners. Moser, Ohmstedt and Rhode (2014) find that patents are also correlated with objective measures for the size of patented inventions, which they collect from field trial data for genetically-modified hybrid corn.

[19] In 1915, 50$\mathcal{M}$ were equal to $10.31 (Bidwell, 1970).

[20] http://www.uspto.gov/web/offices/ac/qs/ope/fee010114.htm; accessed March 2, 2014.

[21] Another benefit of using the median value of five years as a cut-off is that our quality measure is unlikely to be affected by a September 19, 1914 decision of Germany's Federal Council (*Bundesrat*) to suspend renewal fees; this suspension lasted nine months. In 1918, the German Patent Office announced that patentees, who wanted to keep their patents had to pay fees for the last four years (*Blatt* 1918, p. 98). As a result, any patent that was renewed for five years or more has been subject to

generally, 14,605 patents were not renewed in the first year (18.35 percent), 18,319 (23.02 percent) were renewed for 10 years or more, and 6,089 (7.65 percent) were renewed for the full 15-year term (Appendix Figure A3).

F. Matching Patents with Firms

To investigate firm-level changes in patenting, we match patents by German inventors with the names of German firms; this process matches 30,499 GPO patents with application years between 1900 and 1930 to 4,814 unique firms. To construct these data, we search the inventor field for all 75,591 German patents for 358 German words to denote firms, such as *Firma*, *Gesellschaft*, *Gesellschaft mit beschraenkter Haftung* or *Aktiengesellschaft*, as well abbreviations (*GmbH* and *Akt.Ges*) and alternative spellings (*G.m.b.H.* or *Actiengesellschaft*). For 30,499 patents that list a firm as an inventor, we combine alternative spellings of the firm's name to create 4,814 unique firm-level identifiers. For example, we connect different abbreviations for *Aktien Gesellschaft für Anilin Fabrikation* and *Akt. Ges. für Anilin Fabrikation*, to create the unique firm-level identifier *agfa*. In another example, we combine alternative spellings of *Griesheim Elektron* and *Griesheim Electron* into *griesheim-elektron*. A total of 28,192 GPO patents cannot be linked to a firm; most of these patents belong to individuals, such as Dr. N. Sulzberger, Berlin who patented a new "*process for preparing azo-dyestuff*" (Patent No. 193,451).

Fifty of 4,814 German firms who were active patentees in chemistry owned at least one US patent that was licensed under the TWEA. The Bayer AG owned 551 US patents that were licensed, the German Badische Anilin und Soda Fabrik (BASF) 308, Meister Lucius 104, Griesheim-Elektron 57, AGFA 38, Cassella 22, and Berlin-Anhaltische Maschinenbau A.G. (BAMAG) 17. Another 43 firms saw between 1 and 12 of their US patents licensed under the TWEA. 12,531 patents by

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the full fees. In the main analysis we address the issue of this suspension, and other war-related disruptions through robustness checks that exclude the war years (1914-1919) from the sample.

these 50 German firms cover 123 subclasses in the German patent system, and 17,968 patents by 4,764 firms without licensed patents cover 202 subclasses.[22]

G. Firm Size

Data on firm size, which we draw from a registry of publicly traded joint stock companies (*Handbuch der Deutschen Aktiengesellschaften* 1911 and 1912) indicate that firms with licensed patents were large compared with other German firms. A total of 4,814 firms applied for at least one chemical patent in Germany between 1900 and 1930; 175 of them (3.6 percent) are listed in the registries of *Aktiengesellschaften* (AGs). Thirty of 50 firms with licensed patents were AGs, compared with 145 of 4,764 other firms (Appendix Table A3). On average, 30 AGs with licensed patents had a nominal capital stock of $108,343, compared with $40,755 for 145 other AGs in our sample (from *Handbuch* 1911 and 1912, in year 2012 dollars).[23] Data on employees are available for 13 AGs with licensed patents and 50 other AGs. On average, AGs with licensed patents had 6,197 employees in 1911 and 1912 (with a median of 1,060, and a standard error of 4,867), compared with 2,466 employees for other 50 German AGs (with a median of 881, and a standard error of 963).

In terms of firm age, firms with and without licensed patents are roughly comparable: The average AG with licensed patents had been incorporated as a joint-stock company in 1893 (with a standard error of 2.6 years). By comparison, the

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[22] Another 28,192 patents by individual inventors cover 208 subclasses. Although individual inventors were less likely to patent in the United States than German firms, some individual inventors may have been affected by compulsory licensing. Analyses at the firm level exclude these data.

[23] Firms with and without licensed US patents report comparable valuations of patents on their balance sheets. Haber (1971, p. 254), however, warns "…when we look at the finance of chemical companies just before and just after the war, we have a woefully small sample, the information is inadequate and the conclusions must necessarily be tentative." Fourteen of 30 firms with licensed patents reported patents among the assets on their balance sheets; four (13.3 percent) of them listed a positive value; eight (26.7 percent) reported a symbolic 1 *Mark* for devalued patented assets. By comparison, 63 of 145 firms without licensed patents reported patents among their assets; 19 (13.1 percent) of them listed a positive value, 43 (29.7 percent) listed a symbolic value of 1 *Mark.*

average AG without licensed patents had been incorporated as a joint-stock company in 1892 (with a standard error of 1.3 years).

We also construct an indicator variable for six firms that formed a cartel-like "community of interest" in the Interessengemeinschaft (IG) Farben on December 25, 1924: AGFA, Bayer, BASF, Hoechst, Griesheim-Elektron, and Chemische Fabrik (vorm. Weiler Ter Meer). The creation of IG Farben left the internal structure of these firms intact, but reduced competition among the participating firms. Haber (1971, pp. 290-91) explains "In the latter half of the 1920s, the German chemical industry employed nearly 0.3 million people, and on this reckoning IG Farben accounted for over a third."[24] Theses changes may in turn have led to unobservable changes in the organization of production that influenced patenting.[25] After 1924, most patents by the six member firms were assigned directly to IG Farben. As an approximation, we assign patents by IG Farben to the original six firms according to the pre-existing distribution of patents between 1910 and 1914 across firms and technology fields (Appendix Table A7). This approach allows us to include IG Farben's in the firm-level analysis but it assumes that the distribution of patenting remained stable after the 1924. As an alternative approach, robustness checks exclude patents with application years after 1924.

III. RESULTS

Comparisons of means indicate that German inventors began to patent *more* in subclasses with licensing after German patents had been licensed to US firms. In 101 subclasses with licensing, counts of German patents by German inventors increased by 53 percent from 10.77 per application year until 1918 to 16.49

[24] Also see Aftalion (2001, p. 138): "The new giant had a workforce of 67,000 people including 1,000 chemists, and accounted for one third of Germany's chemical industry sales"

[25] For example, Haber (1971, p. 285-86) reports that, after the creation of IG Farben, "the Leverkusen works of Bayer increased their make of dyes by over a quarter, …Hoechst was assigned responsibility for all chemicals from acetylene, and in this connexion (sic) took over the Griesheim patents and technique for polyvinyl acetate manufacture… Bayer became the concern's principal manufacturer of the azo-group of dyes…Badische became the specialist in high –pressure synthesis in all its aspects."

afterwards (Table 1, Panel A). By comparison, in 111 subclasses without licensing, patents increased by less than 10 percent from 5.05 per year until 1918 to 5.54 afterwards.

Although subclasses with licensing produced more patents per year, changes in patenting followed a comparable trend in subclasses with and without licensing until 1918 (Figure 1, Panel A). After 1919, German inventors began to produce more patents in subclasses with licensing, while patents in subclasses without licensing stayed relatively flat. To investigate these changes more systematically, we estimate:

$$(1)\ patents_{ct} = \beta_0 + \beta_1 \bullet subclass\ with\ licensed\ patents_c \bullet post_t + \beta_2 \bullet patents\ by\ US\ inventors_{ct} + \beta_3 \bullet patents\ by\ other\ foreign_{ct} + \delta_t + \theta_c + \varepsilon_{ct}$$

where the dependent variable $patents_{ct}$ measures the number of German patents in subclass *c* and application year *t* between 1900 and 1930. The variable *subclass with licensed patents* equals 1 for subclasses in which at least one German-owned patent was licensed under the US TWEA. The variable $post_t$ indicates years after 1918. Under the assumption that – in the absence of compulsory licensing under the US TWEA - changes in patenting in subclasses with licensing would have been comparable to changes in patenting in subclasses without licensing, the coefficient β_1 measures the effect of compulsory licensing on German invention.

Three variables control for idiosyncratic variation in research activity and patenting ("hotness") across research fields and over time. The variable $patents\ by\ US\ inventors_{ct}$ and $patents\ by\ other\ foreign\ inventors_{ct}$ count patents in Germany by US and other foreign inventors, respectively, in subclass *c* and year *t*. Subclass fixed effects θ_c control for variation in patenting across research fields that is constant over time. Year fixed effects δ_t control for variation in patenting over time that affects all research fields. Standard errors are clustered at the level of subclasses.

OLS estimates indicate that German inventors applied for 2.97 additional patents per year after 1918 in subclasses with licensing (Table 2, column 1, p-value

0.001). Compared with an average of 10.77 patents per year until 1918 for subclasses with licensing, this implies a 28 percent increase. Excluding controls for GPO patents by foreign inventors increases the coefficient to 5.22 additional patents (Table 2, column 2, p-value 0.001).

Comparisons across subclasses with small and large numbers of licensed patents indicate a differential increase in patenting for subclasses with 10 or more licensed patents (Figure 1, Panel B). Until 1918, changes in patenting were similar in subclasses with small and large numbers of licensed patents. After 1918, patenting accelerated disproportionately in subclasses with 10 or more licensed patents. In 1928, inventors applied for an average of 38.4 patents per year in subclasses with 10 or more licenses, compared with 17.41 in subclasses with 3 to 10 licenses, 11.92 in subclasses with 2 licenses and 6.17 patents in subclasses with fewer than 2 licenses. Specifications with a count variable for the number of $\textit{licensed patents}_c$ indicate that – for each additional patent that was licensed in subclass *c* - German inventors applied for 0.20 additional patents per year after 1918 (Table 2, column 5, p-value 0.005). This implies a 33.5 percent increase for the average subclass with at least one licensed patent, which includes 18.04 licensed patents.

A. Controlling for Differential Pre-Trends

We also estimate the effect of compulsory licensing, allowing for subclass-specific linear pre-trends in patenting

$$\text{(2) } \textit{patents}_{ct} = \beta_0 + \beta_1 \bullet \textit{subclass with licensed patents}_c \bullet \textit{post}_t + \beta_2 \bullet \textit{patents by US inventors}_{ct} + \beta_3 \bullet \textit{patents by other foreign}_{ct} + \Sigma_c\, \phi_c \bullet \textit{subclass}_c \bullet \textit{preTWEA}_t \bullet t + \delta_t + \theta_c + \varepsilon_{ct}$$

where $\textit{subclass}_c$ is a vector that distinguishes the 212 GPO subclasses of chemical inventions, the indicator variable $\textit{preTWEA}_t$ equals 1 for years before 1919, and the variable *t* denotes a linear time trend. Estimates with subclass-specific pre-trends indicate that German inventors applied for 5.32 additional patents per year after 1918 in subclasses with licensing (Table 2, column 3, p-value <0.001), which implies a 49 percent increase.[26]

Alternative specifications control for a separate linear pre-trend in patenting for subclasses with licensing:

$$(3)\ patents_{ct} = \beta_0 + \beta_1 \bullet subclass\ with\ licensed\ patents_c \bullet post_t + \beta_2 \bullet patents\ by\ US\ inventors_{ct} + \beta_3 \bullet patents\ by\ other\ foreign_{ct} + \beta_4 \bullet subclass\ with\ licensed\ patents_c \bullet preTWEA_t \bullet t + \delta_t + \theta_c + \varepsilon_{fct}$$

These regressions indicate an increase by 5.02 additional patents per year after 1918 (Table 2, column 4, p-value <0.001), larger than the baseline estimate of 2.97.

B. Excluding the War Years

We also estimate the baseline model (in equation 1) excluding the war years (1915-1918), when patenting may have been influenced by changes in the demand for war-related chemicals, such as explosives and dyes. Estimates that exclude data for the war years are slightly larger than the baseline estimate of 2.97 additional patents (Table 2, column 1). OLS estimates indicate that German inventors applied for 3.22 additional patents in subclasses with compulsory licensing per year after 1918 (Appendix Table A4, column 1, p-value 0.001). Excluding controls for GPO patents by foreign inventors increases the size of this estimate to 5.36 (Appendix Table A4, column 2, p-value 0.001). Intensity specifications indicate that - for each additional *licensed patent*$_c$ - German inventors applied for 0.19 additional patents per year after 1918 (Appendix Table A4, column 5, p-value 0.007), implying a 32 percent increase for the average subclass with at least one licensed patent.

C. Intent-to-Treat and Instrumental Variable Regressions

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[26] We also estimate β_1 separately for each year with 1918 to 1921 as the omitted category. Estimates of annual effects yield no evidence of differential pre-trends. Until 1917, effects are negative and statistically significant only for 4 of 18 years. After 1918 effects are positive and statistically significant for 5 of 12 years. Estimates increase after 1923, with 3.58 additional patents in 1924 and 3.68 in 1925, implying a 33 and 34 percent increase, respectively (with p-values of 0.006 and 0.013).

As a response to Germany's military aggression, the confiscation of all German-owned US property and the timing of the TWEA were exogenous to changes in patenting after 1918. The research fields in which US firms chose to *license* confiscated US patents, however, may not have been exogenous. For example, US firms may have been more likely to license German-owned patents in research fields in which post-war demand for innovation was high. Then, OLS overestimates the increase in innovation. Conversely, OLS underestimates the effects of compulsory licensing if US firms were more likely to license German-owned patents in war-related research fields, such as dyes or explosives, for which demand declined markedly after 1919. For example, Haber (1971, p. 251) explains: "Without demand for war-related chemicals, the worst problem that German dye producers…faced turned out to be excess capacity." Consistent with the idea of negative selection, the subclass with the largest number of licensed patents was 22a for azo dyes, with 436 licensed patents (Appendix Table A5). Patents by German inventors for azo dyes declined from 28.79 per year until 1918 to 24.17 afterwards.

To investigate these issues, we estimate intent-to-treat (ITT) regressions with *subclasses with confiscated patents* - in which German-owned patents were available for licensing - as a treatment variable instead of *licensed patents*:

$$(4)\ patents_{ct} = \beta_0 + \beta_1 \bullet subclass\ with\ confiscated\ patents_c \bullet post_t + \beta_2 \bullet patents\ by\ US\ inventors_{ct} + \beta_3 \bullet patents\ by\ other\ foreign_{ct} + \delta_t + \theta_c + \varepsilon_{ct}$$

where *subclass with confiscated patents*$_c$ is equal to 1, if subclass c includes at least 1 German-owned patent that was confiscated under the TWEA. ITT estimates imply that German inventors applied for 2.36 additional patents per year after 1918 in subclasses with confiscated patents (Table 3, column 1, p-value 0.004). Compared with an average of 10.77 patents per subclass and year until 1918, this implies a 22 percent increase.

Consistent with historical evidence of negative selection (e.g., Haber 1971, p. 251), ITT estimates suggest that OLS may underestimate the effects of compulsory licensing. At 2.36 (Table 3, column 1), ITT estimates are 33 percent larger than 1.78, the product of the OLS estimate of 2.97 (Table 2, column 1) and 0.60, the probability that at least one patent in a subclass with at least 1 confiscated patent was licensed to a US firm.[27]

IV regressions that use *subclasses with confiscated patents*$_c$ as an instrument for *subclasses with licensed patents*$_c$ confirm that OLS is downward biased. First stage regressions indicate that *subclasses with confiscated patents* are 58 percent more likely to be a *subclass with licensed patents* (Table 3, column 4, p-value < 0.001). IV estimates indicate that German inventors applied for 4.05 additional patents per year after 1918 in subclasses with licensing (Table 3, column 6, p-value < 0.001), compared with 2.97 additional patents implied by OLS (Table 2, column 1). The local average treatment effect of 4.05 in the IV regressions estimates the effect of making German-owned US patents available to US firms for technologies that German inventors chose to patent in the United States between 1900 and 1918. These technologies are more likely to be relevant for the US market, and due to the costs of patenting abroad they are more likely to be owned by larger German firms.[28]

IV. Mechanisms

In this section we explore alternative channels by which compulsory licensing may have encouraged patenting and innovation. First, we use renewal data to examine whether German inventors responded to the loss of their US patents by reinforcing their German patents through a patent thicket of lower quality, or

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[27] Among 212 subclasses of chemical inventions, 167 subclasses include at least one confiscated patent; 101 of these 167 subclasses with confiscated patents include at least one licensed patent. ITT estimates with patents that were renewed for at least 5 years imply a 19 percent increase in patenting in GPO subclasses with confiscated patents (Appendix Table A6, column 1).

[28] See the description of the firm characteristics in the data section and Appendix Table A.3.

strategic patents (Shapiro 2001, Hall and Ziedonis 2001).[29] This test suggests an increase in lower quality patents, which is, however, not large enough to account for the observed increase. Then, we examine firm-level data on changes in patenting to explore the potential effects of compulsory licensing on entry and on incumbents whose patents had been licensed.

A. Strategic Patenting

Estimates with patents that had been renewed for a minimum of five years indicate that the observed increase in patenting is robust to controlling for patent quality, even though a small part of the observed increase may have been due to lower quality strategic patents. Similar to raw patents, counts of renewed patents per year follow a similar trend for subclasses with and without licensing until 1918 (Appendix Figure A4, Panel A). After 1918, renewed patents increased in subclasses with licensing but stayed flat in other subclasses. In 1927, German inventors applied for 9.63 renewed patents in subclasses with licensing, more than three times compared with 2.29 renewed patents in other subclasses. In subclasses with licensing, counts of renewed patents increased by 28 percent from 6.28 per year until 1918 to 8.05 afterwards (Table 1, Panel A). By comparison, in subclasses without licensing, renewed patents declined by 12 percent from 2.56 per year until 1918 to 2.28 afterwards.

Estimating the baseline specification (equation 1) with renewed patents as an outcome variable indicates that German inventors applied for 1.09 additional renewed patents per year after 1918 in subclasses with licensing (Table 2, column 7, p-value 0.02). Compared with an average of 6.28 renewed patents per subclass and year until 1918, this implies a 17 percent increase. Estimates with subclass-specific

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[29] Shapiro (2001, p. 120) vividly defines a "patent thicket" as a "dense web of overlapping intellectual property rights that a company must hack its way through in order to actually commercialize new technology." Hall and Ziedonis (2001) study of 95 US semiconductor firms between 1979 and 1995 shows that firms build portfolios of strategic patents to use against each other in case of litigation.

pre-trends indicate that German inventors applied for 2.35 additional renewed patents (Table 2, column 8, p-value 0.001), implying a 37 percent increase. Regressions with a separate trend in patenting for subclasses with licensing indicate that German inventors applied for 2.26 additional renewed patents per subclass and year, implying a 36 percent increase (not reported). Intensity regressions indicate that – for each additional *licensed patent*$_c$ in subclass *c* - German inventors applied for 0.08 additional renewed patents per year after 1918; this implies a 23 percent increase for the average subclass with at least one licensed patent (not reported).

B. Entry into Fields with Licensing

US patent data indicate that German inventors faced increased competition from *US inventors*, who became significantly more productive in subclasses with licensing (Moser and Voena 2012). German patent data confirm the significant differential increase in US invention in research fields with licensing (Data Section II.D, Figure 2). This increased presence of US inventors created a threat of competition, which may have encouraged incumbent patentees to innovate more.

In this section, we examine whether firms whose patents had been licensed also faced increased competition from *German inventors* in research fields with licensing. Firm-level data reveal a large increase after 1918 in the number of German firms that were active in research fields with licensing. Until 1918, an average of 2.29 firms without licensed patents produced patents in subclasses with licensing; after 1918 this number increased by 70 percent to 3.90 firms (Table 5). By comparison, the average number of firms without licensed patents that produced patents in subclasses without licensed patents increased only by 23 percent, from 1.22 to 1.50. After 1918, entrants without previous patents in subclasses with licensing account for 5,065 of 12,852 German-owned (39 percent) in subclasses with licensing.

The Deutsche Gold- und Silber-Scheide-Anstalt (Degussa) is an example of a German firm that entered research fields with licensing after 1918. Until 1918, Degussa had applied for a total of 58 patents across 10 subclasses of chemical inventions, including 54 patents in 8 subclasses with licensing. After 1918, Degussa applied for a total of 147 patents, including 83 patents in the same 8 subclasses with licensing, 24 in subclasses without licensing, and 50 patents in 12 subclasses with licensing, in which Degussa had not patented until 1918.

The example of Degussa suggests that some of the increase in patenting in fields with licensing may have been driven by a shift in the direction of invention, as firms that had been active in other fields switched into fields with licensing after 1918.

To investigate whether the observed increase in patenting in subclasses with licensing was driven by firms that *switched* into subclasses with licensing from other fields of chemical research, we measure the share of patents in subclasses with licensing by firms with previous patents in other subclasses of chemicals (switchers) and firms without previous patents (entrants into chemical research). These comparisons reveal that the increase in patenting by entrants in subclasses with licensing was driven primarily by entrants *without* previous patents for chemicals. Entrants without previous patents *in any field of chemical research* account for 2,898 of 5,065 patents (57 percent) by firms without previous patents with licensing.[30]

C. Firm-level Changes in Patenting

To investigate the mechanism by which compulsory licensing may encourage invention, we examine changes in patenting after 1918 for German firms that were differentially affected by compulsory licensing under the US TWEA. Summary

[30] Patents per year by firms *without* pre-1919 patents in other fields of chemical research increased from 1.45 in 1919 to 2.96 in 1924 and 2.91 in 1929 (Appendix Figure A5). By comparison, the average number of patents by entrants *with* pre-1919 patents declined from 1.28 in 1919 to 1.85 in 1924 and 1.82 in 1929.

statistics indicate that German firms with licensed patents began to patent more in research fields in which their US patents had been licensed (Table 1, Panel B).

Baseline regressions compare changes in patents per subclass and year after 1918 for German firms whose patents had become subject to compulsory licensing with changes for other German firms. Triple differences regressions estimate:

$$(5)\ patents_{fct} = \gamma_0 + \gamma_1 \bullet subclass\ w\ licensed\ patents_c \bullet firm\ w\ licensed\ patent_f \bullet post_t$$
$$+ \gamma_2 \bullet subclass\ w\ licensed\ patents_c \bullet post_t + \gamma_3 \bullet firm\ w\ licensed\ patent_f \bullet post_t$$
$$+ \gamma_4 \bullet subclass\ w\ licensed\ patents_c \bullet firm\ w\ licensed\ patent_f$$
$$+ \gamma_5 \bullet patents\ by\ US\ inventors_{ct} + \gamma_6 \bullet patents\ by\ other\ foreign_{ct}$$
$$+ \gamma_7 \bullet patents\ by\ individuals_{ct} + \delta_t + \theta_c + \lambda_f + \varepsilon_{fct}$$

where the outcome variable $patents_{fct}$ counts patents by firm f in subclass c and application year t. The variable $firm\ w\ licensed\ patent_f$ equals 1 if at least one of firm f's patents was licensed. The variable $patents\ by\ individuals_{ct}$ counts patents in subclass c and year t by individual German inventors; all other control variables are as defined above. The triple difference coefficient γ_1 measures the effect of compulsory licensing on firms whose patents were licensed, compared with other German firms. It is unbiased if - in the absence of compulsory licensing - changes in patenting in subclass c after 1918 would have been comparable for German firms with and without licensed patents.

This analysis indicates that firms, whose patents had been licensed, applied for 0.42 additional patents per year after 1918 in subclasses with licensing (Table 4, column 1, p-value 0.002). Compared with a mean of 0.46 patents per subclass and year until 1918 for firms with licensed patents, this implies a 91 percent increase in patenting. These results are robust to including subclass-specific pre-trends (Table 4, column 2).

Robustness checks exclude patents with application years after 1924, the last year before the creation of the cartel-like IG Farben. These tests take into account that the formation of IG Farben may have affected the structure of competition within the German chemical industry. Estimates with the restricted sample of patent applications until 1924 confirms that firms whose patents had been licensed increased their patenting activity after 1918. Baseline estimates indicate that firms whose patents had been licensed applied for 0.16 additional patents after 1918 in fields with licensing (Table 4, column 3, p-value 0.002). Compared with an average of 0.46 patents per subclass and year until 1918 for firms with licensed patents, this implies a 35 percent increase. Regressions with subclass-specific pre-trends indicate a slightly larger increase of 0.17 additional patents per year after 1918 (Table 4, column 4, p-value 0.002), which implies a 37 percent increase. Excluding data after 1924 may, however, lead us to under-estimate firms' response to compulsory licensing, if effects of compulsory licensing occur with some delay. For US inventors, the strongest increase in patenting occurred six years after the first licenses were issued, which is consistent with a prolonged period of learning (Moser and Voena 2012, p. 409). For example, Du Pont's early runs of indigo blue turned out green (Hounshell and Smith 1988, p.90). If similar delays affected German firms, regressions that drop years after 1924 underestimate the effects of compulsory licensing.

Regressions with renewal data imply a smaller, albeit substantial increase. German firms applied for 0.29 additional renewed patents after 1918 in subclasses in which their patents had been licensed (Table 4, column 5, p-value < 0.001). Relative to an average of 0.39 renewed patents per subclass and year until 1918 for firms with licensed patents, this implies a 74 percent increase. Estimates with subclass-specific pre-trends indicate that German firms applied for 0.30 additional renewed patents in subclasses, in which their patents had been licensed (Table 4, column 6, p-value < 0.001), which implies a 77 percent increase. Regressions that allow for a separate trend for firms with licensing indicate that German firms applied for 0.29 additional renewed patents per year in subclasses in which their patents had been licensed; this implies a 74 percent increase (not reported).

D. Inverted-U?

To test the predictions in Aghion et al. (2001, 2005), we compare the effects of compulsory licensing across research fields with high and low levels of competition. We measure variation in competition through the Herfindahl-Hirshman index (HHI) of patents per technology field and year:

$$\text{HHI}_{ct} = \frac{(\Sigma_i \ p_{ict})^{-1}/F_{ct}}{1-1/F_{ct}}$$

where p_{ict} is firm *i*'s share of total patents in subclass *c* and year *t,* and F_{ct} measures the number of patent-active firms in subclass *c* and year *t*. Comparisons of patent counts for 3,265 subclass-year pairs show that most subclasses are relatively competitive: Two-thirds of all subclass-year pairs have an HHI of 0.1 or less (Figure 3). Similar to plots of patent counts across UK industries in Aghion et al. (2005), the data are also broadly consistent with an inverted U-shaped relationship between competition and innovation.[31]

To compare the effect of compulsory licensing across subclasses with low and high levels of pre-existing competition, we re-estimate the baseline specification (equation 2) with an additional interaction term between the difference-in-differences estimator and a set of indicator variables for deciles of the HHI for years until 1918:

$$\begin{aligned}(6)\ patents_{ct} = {} & \alpha + \Sigma_d\, \beta_d \bullet subclass\ w\ licensed\ patents_c \bullet pre\text{-}1919\ HHI\ decile_d \bullet post_t \\ & + \Sigma_d\, \gamma_d \bullet pre\text{-}1919\ HHI\ decile_d \bullet post_t + \zeta_1 \bullet subclass\ w\ licensed\ patents_c \bullet post_t \\ & + \zeta_2 \bullet patents\ by\ US\ inventors_{ct} + \zeta_3 \bullet patents\ by\ other\ foreign_{ct} + \delta_t + \theta_c \\ & + \Sigma_c\, \phi_c \bullet subclass_c \bullet preTWEA_t \bullet t + \varepsilon_{ct}\end{aligned}$$

where the 5^{th} and 6^{th} decile of the HHI, which include the median subclasses, are the omitted categories. Estimates increase from 8.22 *fewer* patents for the 10^{th} decile

[31] Figure 3 is most similar to Figure 1 in Aghion et al. 2005, which plots patents per industry and year against (1-) the Lerner index as a measure for the intensity of competition. Estimates with the HHI and the concentration ratio (C4, not reported) are also consistent with Levin, Cohen, and Mowery's (1985) findings that competition and innovation are positively correlated up to the 5^{th} and 6^{th} decile of the C4 in FTC line of business data. Levin et al. (1985) find that this correlation disappears with controls for variation across industries in the effectiveness of mechanisms to appropriate the returns from R&D. The current study investigates differences in competition *within* chemicals, an industry, in which patents were an effective mechanism to appropriate returns from R&D (Moser 2012).

(Appendix Figure A6, p-value of 0.26) to 14.74 *additional* patents for the 7th decile (p-value of 0.11). Estimates are close to zero for the 4th to the 1st decile of the HHI. These estimates suggest that the observed increase in patenting was driven by technologies in which patenting was relatively concentrated before 1919. By comparison, the effects of compulsory licensing appear to have been much weaker for technologies in which invention had already been competitive prior to compulsory licensing.

V. Conclusions

This paper has used a new data set of 79,591 chemical patents in Germany between 1900 and 1930 to examine the effects of compulsory licensing under the WWI Trading with the Enemy Act on German invention. Under the TWEA, all German-owned US patents became subject to compulsory licensing in 1919. We find that compulsory licensing encouraged, rather than discouraged invention in Germany. German inventors produced 28 percent more patents after 1918 in research fields with licensing. Intent-to-treat regressions and instrumental variable regressions, which use subclasses with confiscations as an instrument for subclasses with licensing, suggest that OLS estimates underestimate the effect of compulsory licensing on German patents.

An analysis of high-quality patents indicates a slightly smaller increase in patenting. This suggests that some of the observed increase in patenting may have been due to an increase in lower quality strategic patents. Estimates, however, remain large and statistically significant, and imply a 17 percent increase in high-quality patents.

Firm-level analyses of patent data reveal a significant increase in the number of research-active firms in research fields with licensing. Nearly 40 percent of all patents after 1918 in fields with licensing were by firms without pre-1918 patents in these fields. Among entrants into fields with licensing, firms without previous patents in any other fields of chemicals produced more patents in fields with licensing after 1918 compared with firms that had been active in other fields of chemical research before 1918. We also find that German firms whose patents had been licensed produced more patents after 1918 in fields in which their patents had been licensed. Taken together, these results indicate that compulsory licensing can promote innovation by encouraging competitors to enter fields with licensing, which increases the threat of competition for incumbent inventors and motivates them to invest more in R&D.

In the early 20th century and today, industries that are most affected by compulsory licensing tend to be relatively concentrated. In 2013, for example, therapies by Gilead, Johnson & Johnson, and Brystol Myers dominated the market for HIV drugs. Gilead's *Truvada* and related drugs accounted for $9 billion in sales, Brystol-Myers *Sustiva* generated $3.6 billion, and *Ruveda* which combines Gilead's drug *Viread* and *Emtriva*, recorded $3.1 billion in sales, while other drugs sold substantially less (Campbell 2014). Our findings suggest that compulsory licensing can encourage innovation in these industries. In fact, we find that compulsory licensing was particularly effective at promoting invention in fields that were *ex ante* more concentrated, and less effective in fields that were competitive already.

It is, however, important to note that the benefits of compulsory licensing depend on the credibility with which national governments can commit to invoke it exclusively in cases of emergencies. Triggered by Germany's military aggression, the 1919 Trading-with-the-Enemy Act was at the time perceived as a one-shot event. We find that incumbent inventors responded by investing heavily in R&D to escape competition with new entrants. Similar to other types of government policies, such as monetary policy and capital taxation (Kydland and Prescott 1977, Fischer 1980), compulsory licensing is however subject to dynamic inconsistency, and firms may invest less in R&D if they expect repeated episodes of compulsory licensing. We conclude that compulsory licensing can *promote* innovation - if governments can credibly commit to using it only in exceptional cases of emergencies.

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TABLE 1 – GPO PATENTS BY GERMAN INVENTORS PER SUBCLASS AND YEAR

PANEL A: SUBCLASSES WITH AND W/O LICENSED PATENTS

	Subclasses with licensed patents		Subclasses without licensed patents		Difference
	N	Mean	N	Mean	
All patents					
1900-1918	101	10.77	111	5.05	5.72
		(1.31)		(0.58)	(1.43)
1919-1930	101	16.49	111	5.54	10.95
		(2.47)		(0.95)	(2.64)
Patents renewed ≥5 years					
1900-1918	101	6.28	108	2.56	3.72
		(0.84)		(0.30)	(0.89)
1919-1930	101	8.05	108	2.28	5.77
		(1.29)		(0.38)	(1.35)

PANEL B: GERMAN FIRMS WITH AND W/O LICENSED PATENTS

	Firms with licensed patents		Other German firms		Difference
	N	Mean	N	Mean	
All patents					
1900-1918	50	0.46	4,764	0.05	0.41
		(0.10)		(0.01)	(0.01)
1919-1930	50	0.94	4,764	0.10	0.84
		(0.23)		(0.01)	(0.01)
Patents renewed ≥5 years					
1900-1918	47	0.39	2,933	0.05	0.34
		(0.08)		(0.01)	(0.01)
1919-1930	47	0.66	2,933	0.09	0.57
		(0.16)		(0.01)	(0.01)

Notes: Data include 58,691 GPO patents by German inventors with application dates between January 1, 1900 and December 31, 1930. *Patents renewed ≥5 years* are 30,017 GPO patents by German inventors that were renewed 5 years or more. *Subclasses with licensed patents* cover 101 technology fields in which at least one German-owned U.S. patent was licensed under the TWEA. *Subclasses without licensed patents* cover 111 remaining technology fields within chemicals without licensed patents. Standard errors are clustered at the subclass level in Panel A and at the firm level in Panel B.

TABLE 2 – OLS, DEPENDENT VARIABLE IS PATENTS PER SUBCLASS AND YEAR

	All Patents (1-6)						Patents renewed≥5y (7-8)	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Subclass with licensed patents*post	2.968***	5.219***	5.317***	5.017***			1.092**	2.345***
	(0.915)	(1.535)	(1.427)	(1.394)			(0.466)	(0.720)
Licensed patents * post					0.196***	0.356***		
					(0.069)	(0.113)		
Licensed patents^2 * post					-0.000***	-0.001***		
					(0.000)	(0.000)		
Patents by U.S. inventors	0.859***		0.700***	0.857***	0.815***	0.667***	0.817***	0.687***
	(0.142)		(0.136)	(0.142)	(0.142)	(0.131)	(0.149)	(0.163)
Patents by other foreign	1.503***		1.353***	1.500***	1.376***	1.233***	1.194***	1.136***
	(0.228)		(0.229)	(0.228)	(0.153)	(0.156)	(0.186)	(0.205)
Standard errors (in parentheses) are clustered at the level of subclasses, *** p<0.01, ** p<0.05, * p<0.1								
Mean in subclasses w licensed patents 1900-18	10.77	10.77	10.77	10.77	10.77	10.77	6.28	6.28
Subclass-specific pre-trends	No	No	Yes	No	No	Yes	No	Yes
Pre-trend for subclasses with licensing	No	No	No	Yes	No	No	No	No
Subclass fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	6,572	6,572	6,572	6,572	6,572	6,572	6,479	6,479

Notes: Data include all 79,591 applications for patents on chemical inventions between 1900 and 1930. Data on renewal decisions come from archival records of renewed patents from the *Annual Reports* of the German patent office between 1901 and 1942. *Subclass with licensed patents* is an indicator variable that equals one for 101 German subclasses, in which at least one US patent became subject to compulsory licensing. The indicator variable *post* equals 1 for all years after 1918. The variable *licensed patents* measures the number of patents that became subject to licensing. *Patents by US inventors* controls for the number of patents that the GPO issued to residents of the United States in subclass *c* and year *t*; *patents by other foreign* controls for the number of patents that the GPO issued to residents of other foreign countries.

TABLE 3 – INTENT-TO-TREAT AND INSTRUMENTAL VARIABLE REGRESSIONS, DEPENDENT VARIABLE IS PATENTS PER SUBCLASS AND YEAR

	Intent to Treat (1-3)			Instrumental Variables (4-7)			
				First stage		IV	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Subclass with confiscated patents * post	2.359***	4.474***	4.264***	0.582***	0.585***		
	(0.808)	(1.324)	(1.331)	(0.014)	(0.014)		
Subclass with licensed patents * post						4.050***	7.652***
						(0.840)	(1.213)
Patents by U.S. inventors	0.886***	0.726***	0.884***	0.010***	0.006***	0.845***	0.683***
	(0.144)	(0.136)	(0.144)	(0.002)	(0.002)	(0.086)	(0.086)
Patents by other foreign	1.517***	1.370***	1.517***	0.006***	0.004***	1.495***	1.340***
	(0.231)	(0.233)	(0.231)	(0.001)	(0.001)	(0.037)	(0.038)
Standard errors (in parentheses) are clustered at the level of subclasses, *** p<0.01, ** p<0.05, * p<0.1							
Mean in subclasses with licensed patents, 1900-18	10.77	10.77	10.77			10.77	10.77
Subclass-specific pre-trends	No	Yes	No	No	Yes	No	Yes
Pre-trend for subclasses with confiscated patents	No	No	Yes	No	No	No	No
Subclass fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	6,572	6,572	6,572	6,572	6,572	6,572	6,572

Notes: Data include all 79,591 applications for patents on chemical inventions between 1900 and 1930. *Subclass with confiscated patents* is an indicator variable that equals one for 171 German subclasses in which at least one U.S. patents was confiscated after the TWEA. *Subclass with licensed patents* is an indicator variable that equals one for 101 German subclasses, in which at least one US patent became subject to compulsory licensing. The indicator variable *post* equals 1 for all years after 1918. *Patents by U.S. inventors* controls for the number of patents that the German Patent Office issued to residents of the United States in subclass *c* and year *t*; *patents by other foreign* controls for the number of patents that the German Patent Office issued to residents of other foreign countries.

TABLE 4 – FIRM-LEVEL OLS, DEPENDENT VARIABLE IS PATENTS PER FIRM, SUBCLASS, AND YEAR

	All Patents and Years		1900-1924		Patents renewed ≥ 5y	
	(1)	(2)	(3)	(4)	(5)	(6)
Subclass w licensed patents * firm w licensed patents * post	0.415***	0.411***	0.155***	0.173***	0.292***	0.300***
	(0.134)	(0.134)	(0.051)	(0.055)	(0.073)	(0.074)
Subclass w licensed patents * post	0.013	0.020**	0.019***	0.024***	0.012	0.016*
	(0.008)	(0.009)	(0.006)	(0.008)	(0.008)	(0.010)
Patents by U.S. inventors	0.004***	0.003***	0.002***	0.002**	0.003***	0.002***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Patents by other foreign	0.006***	0.006***	0.003***	0.003***	0.005***	0.005***
	(0.002)	(0.002)	(0.001)	(0.001)	(0.002)	(0.002)
Patents by individuals	0.002***	0.002***	0.003***	0.003***	0.002***	0.002***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Standard errors (in parentheses) are clustered at the level of firms, *** p<0.01, ** p<0.05, * p<0.1						
Mean for firms with licensed patents, 1900-18	0.46	0.46	0.46	0.46	0.46	0.46
Subclass-specific pre-trends	No	Yes	No	Yes	No	Yes
Pre-trend for firms with licensing	No	No	No	No	No	No
Subclass fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Firm fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
N (Subclass-firm-year)	274,133	274,133	221,075	221,075	164,207	164,207

Notes: Regressions also include *firms w licensed patents * post, licensed patents * firms w licensed patents*, and *subclass w licensed patents * firms w licensed patents.* Data include all 79,591 German patents on chemical inventions for 8,843 firm-subclass pairs, with application years between 1900 and 1930. *Firm w licensed patents* equals 1 for 50 German firms that owned at least 1 US patent that became subject to compulsory licensing. The indicator variable *post* equals 1 for years after 1918. *Subclass w licensed patents* is an indicator variable that equals one for 101 German subclasses, in which at least one US patent became subject to compulsory licensing. *Patents by US inventors* controls for GPO patents to US residents in subclass *c* and year *t*; *patents by other foreign* and *patents by individuals* control for GPO patents to other foreign and individual (non-firm) inventors, respectively.

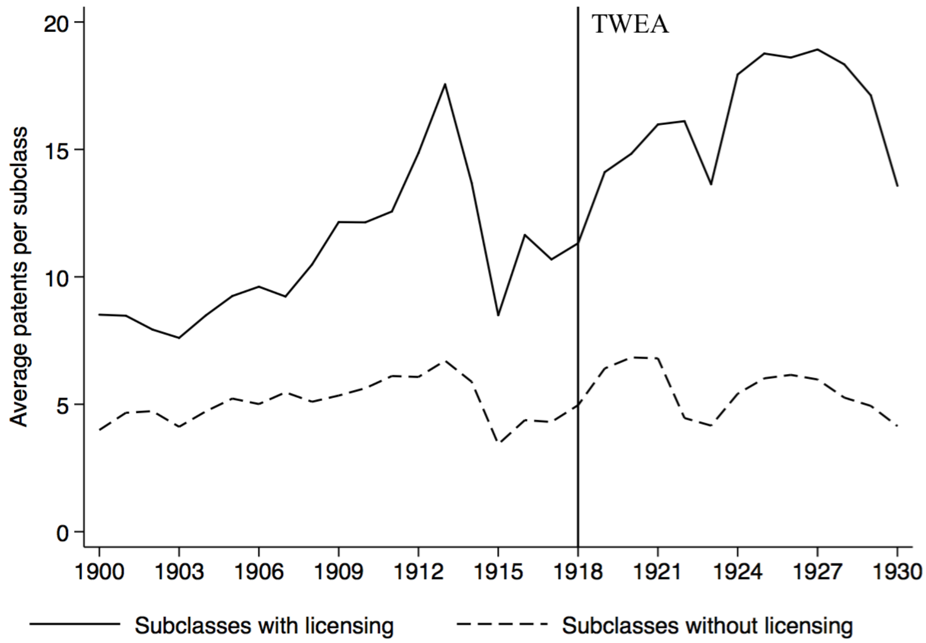
TABLE 5 –FIRMS PER SUBCLASS AND YEAR

	Subclasses with licensed patents		Subclasses without licensed patents		Difference
	N	Mean	N	Mean	
1900-1918	101	2.29	111	1.22	1.07
		(0.22)		(0.14)	(0.26)
1919-1930	101	3.90	111	1.5	2.40
		(0.46)		(0.24)	(0.56)
Difference		1.61		0.28	1.33
		(0.32)		(0.17)	(0.36)

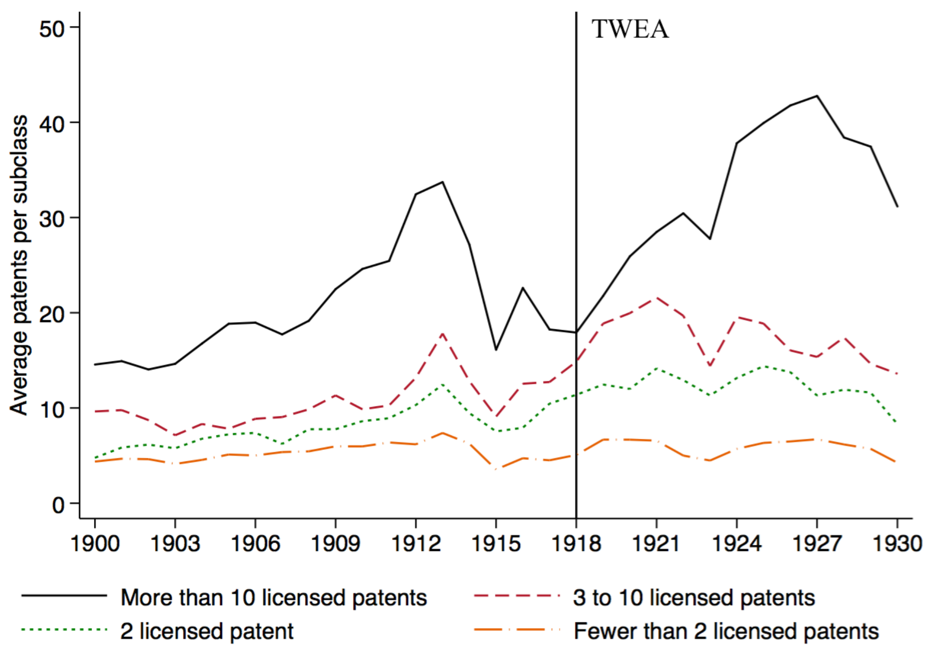
Notes: Counts of German firms per subclass and year for firms without licensed patents; standard errors in parentheses. A total of 4,764 German firms without licensed patents applied for 58,691 patents for chemical inventions between January 1, 1900 and December 31, 1930. 101 *subclasses with licensed patents* cover technologies for which at least 1 US patent by another German firm was licensed under the TWEA; 111 *subclasses without licensed patents* did not include any licensed patents.

FIGURE 1 – GERMAN-OWNED PATENT APPLICATIONS PER SUBCLASS AND YEAR

PANEL A – SUBCLASSES WITH AND WITHOUT LICENSED PATENTS

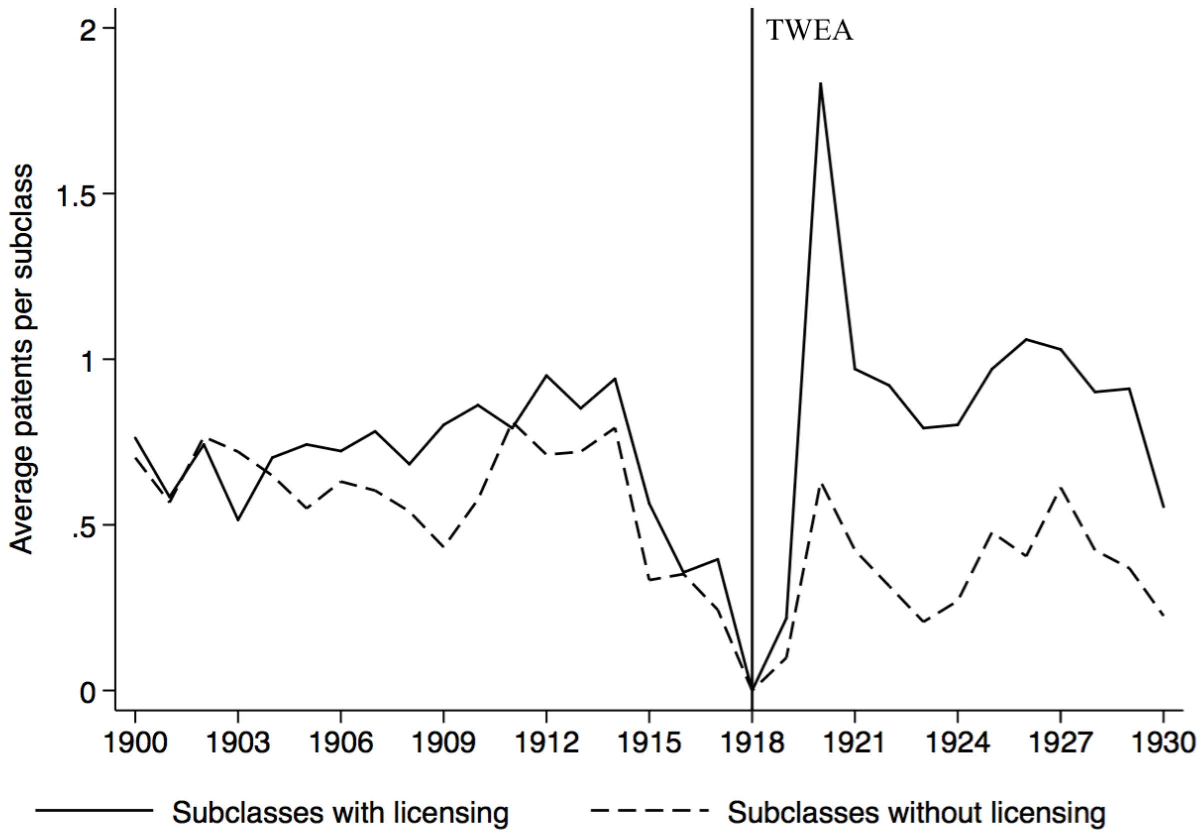


PANEL B – QUARTILES OF THE DISTRIBUTION OF LICENSED PATENTS



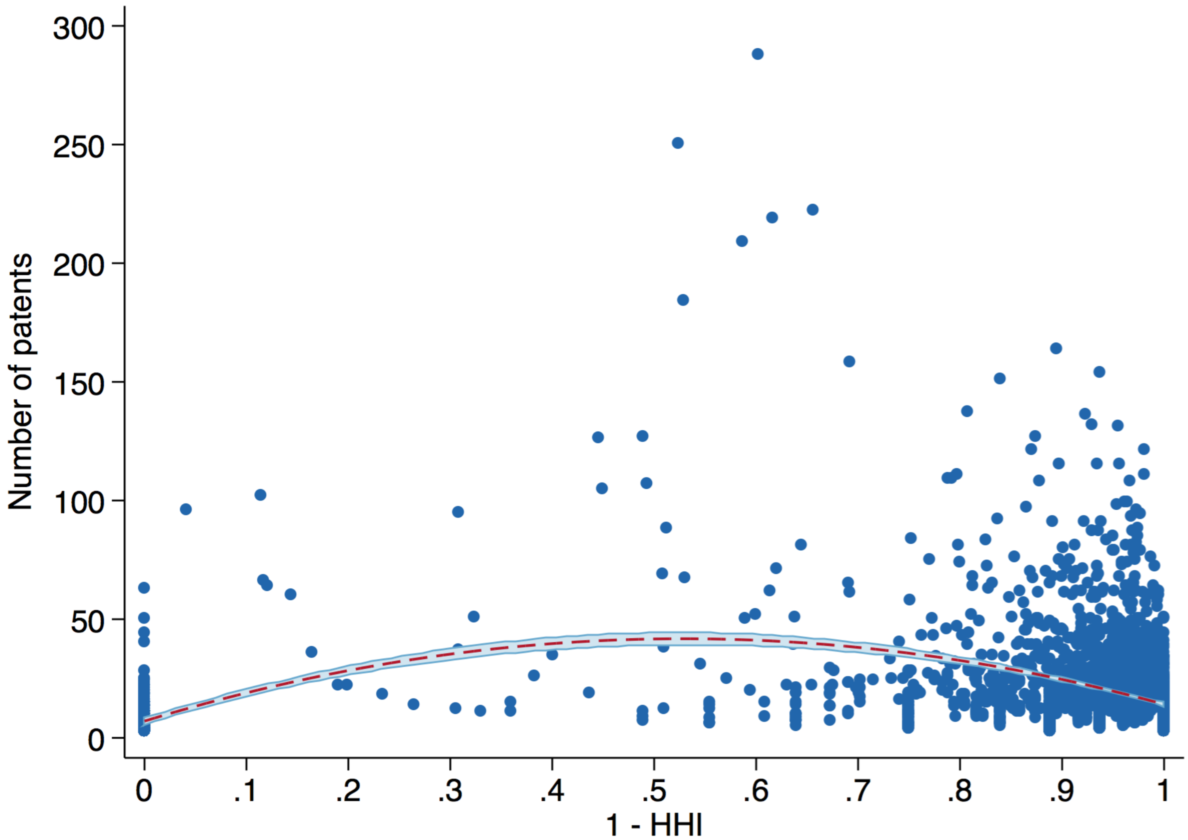
Notes: Data include 58,691 GPO patents by German inventors with application years between January 1, 1900 and December 31, 1930. We have collected these data from the GPO's Annual Report (*Verzeichnis der im Vorjahre erteilten Patente*) between 1900 and 1932. 101 *subclasses with licensing* each include at least one US patent by a German firm was licensed under the TWEA; 111 *subclasses without licensing* include no licensed patents.

FIGURE 2 – US-OWNED PATENT APPLICATIONS PER SUBCLASS AND YEAR



Notes: Data include 4,133 GPO patents by US inventors with application years between January 1 1900 and December 31, 1930, which we collected from the Annual Report of the GPO (*Verzeichnis der im Vorjahre erteilten Patente*) between 1900 and 1932. 101 *subclasses with licensing* correspond to technologies in which at least one German-owned US patent was licensed to a US firm under the TWEA; 111 *other subclasses without licensing* include no licensed patents.

FIGURE 3– INNOVATION (PATENTS) ON COMPETITION (1-HHI)



Notes: Data include all 79,591 applications for patents on chemical inventions between 1900 and 1930. Each observation is a subclass-year pair for (1-HHI of patents per subclass, firm and year; patents per subclass and year). The figure plots 1-HHI against the total number of patents per subclass and year. HHI is the normalized Herfindahl–Hirschman Index and is computed as $\frac{(\sum_i^F p_i^2 - 1/F)}{1 - 1/F}$, where p_i is the patent share of firm i in each subclass and F is the number of patent-active firms. The interrupted red line plots a 2nd order polynomial with 95 percent confidence intervals to fit the data.

ONLINE APPENDIX

NOT FOR PUBLICATION

TABLE A1 – CONCORDANCE BETWEEN THE USPTO AND GERMAN PATENT SYSTEM

	Licensed patents (N = 1,246)	Confiscated patents (N = 4,706)
US patents matched with at least one GPO subclass	968	3,533
1) USPTO-IPC-GPO concordance		
All patents matched	954	3,464
USPTO-IPC-GPO concordance only	869	3,103
2) USPTO & GPO patents for the same invention		
All patents matched	99	430
USPTO & GPO for the same invention only	14	69

Notes: Licensed patents are 1,246 German-owned patents, which the US Alien Property Custodian made available for licensing; *confiscated patents* are 4,706 German-owned US patents, which were available for licensing (from Haynes 1945, p. 498 and Alien Property Custodian 1919, p. 437). The USPTO-IPC concordance matches 7,699 USPTO subclasses with 7,010 subclasses in the International Patent Classification (IPC). Another concordance, made available by the GPO (Figure A1), matches IPC subclasses with 513 GPO subclasses; combining these two concordances creates the USPTO-IPC-GPO concordance. To improve this classification we match subclasses across the USPTO and GPO system, using information on 1,343 USPTO and GPO patents for the same invention; this matching exploits a requirement to record the application date of USPTO patents after Germany ratified the Paris Convention in 1903. We use this requirement to identify USPTO and GPO patents that cover the same invention.

FIGURE A1 – CONCORDANCE BETWEEN THE GERMAN PATENT SYSTEM AND THE INTERNATIONAL PATENT CLASSIFICATION

DPK		IPC	
1A	3	B03B	3-16
1A	3-00	B03B	3-16
1A	4	B03B	3-28
		B03B	11-00
1A	6-00	B03B	3-32
1A	7	B03B	3-34
1A	9	B03B	3-12
1A	10	B03B	3-08
1A	12-01	B03B	3-30
1A	12-10	B03B	3-30
1A	13	B03B	3-00
		B03B	3-02
		B04B	3-00

Notes: Excerpt from the concordance scheme between the International Patent Classification (IPC) and the classification system of the German Patent Office (DPK).

TABLE A2 – LICENSED AND CONFISCATED PATENTS PER GPO SUBCLASS

	All Subclasses		Subclasses with at least 1 licensed patents	
	N	Mean	N	Mean
Licensed patents	212	8.59	101	18.04
		(38.02)		(53.65)
Confiscated patents	212	19.51	101	37.56
		(47.66)		(64.33)

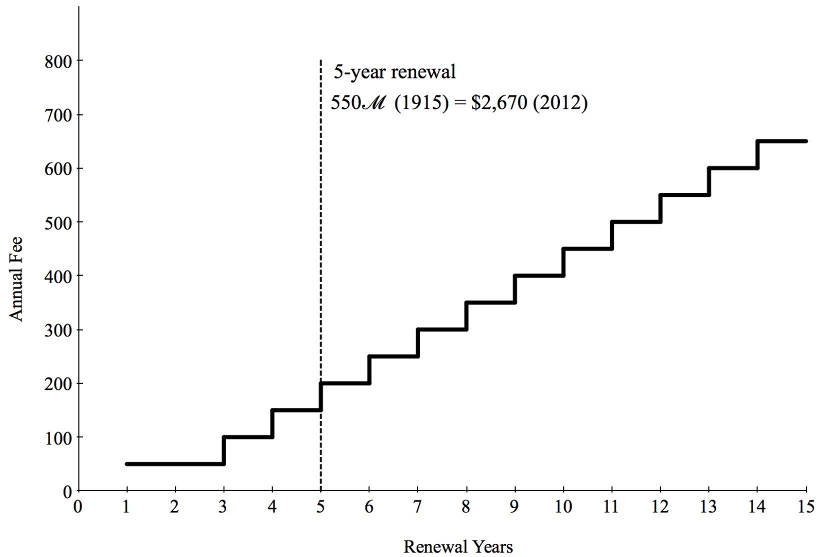
Notes: *Licensed patents* counts German-owned US patents that were licensed under the TWEA in each GPO subclass. *Confiscated patents* measures the number of patents that were seized by U.S. authorities after the Trading With the Enemy Act in each GPO subclass. Standard deviations in parentheses.

TABLE A3 – GERMAN JOINT STOCK COMPANIES

	German firms with licensed US patents		Other German firms		P-value
	N	Mean	N	Mean	
Nominal capital stock (in year 2012 US$)	30	108,343	145	40,755	0.097
		(38,284)		(8,253)	
Employees	13	6,197	50	2,466	0.475
		(4,867.71)		(963.42)	
Year of incorporation	30	1893	145	1892	0.613
		(2.61)		(1.37)	

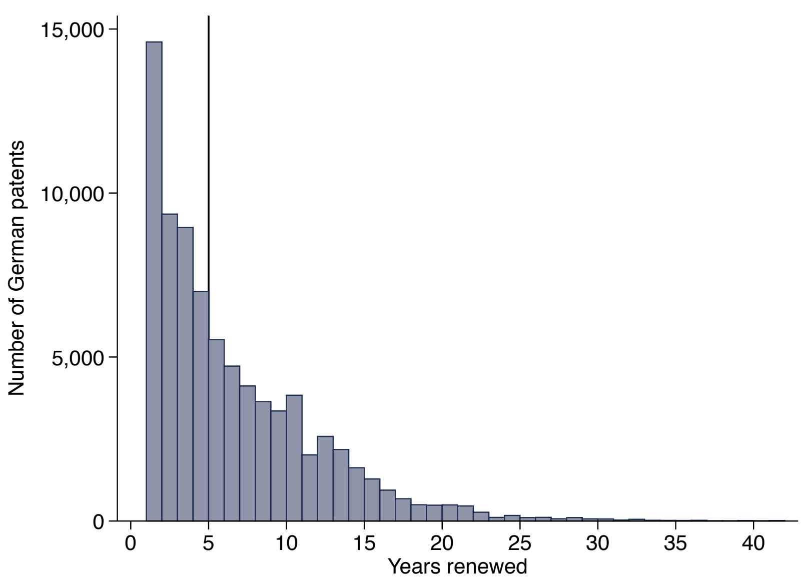
Notes: Joint stock companies (*Aktiengesellschaften*, or AGs) are corporations that are owned by shareholders, who can trade their shares on the stock market. 175 of 4,814 firms are listed in the registries of German AGs, (*Handbuch der Deutschen Aktiengesellschaften*, 1911 and 1912). Year of incorporation refers to the year in which the firm was incorporated as a joint stock company. Standard errors clustered at the firm level in parentheses.

FIGURE A2 – RENEWAL FEE STRUCTURE



Notes: In the first two years, renewal fees were 50ℳ per year, roughly 243 2012 dollars using purchasing power conversions (Williamson 2014). Beginning in the third year, renewal fees per year increased by 50ℳ each year, reaching a total of 700ℳ in the final 15th year of patent life. Patents that were renewed for 5 years or more required inventors to pay a minimum of 550ℳ in renewal fees, $2,670 year 2012 dollars using purchasing power conversions.

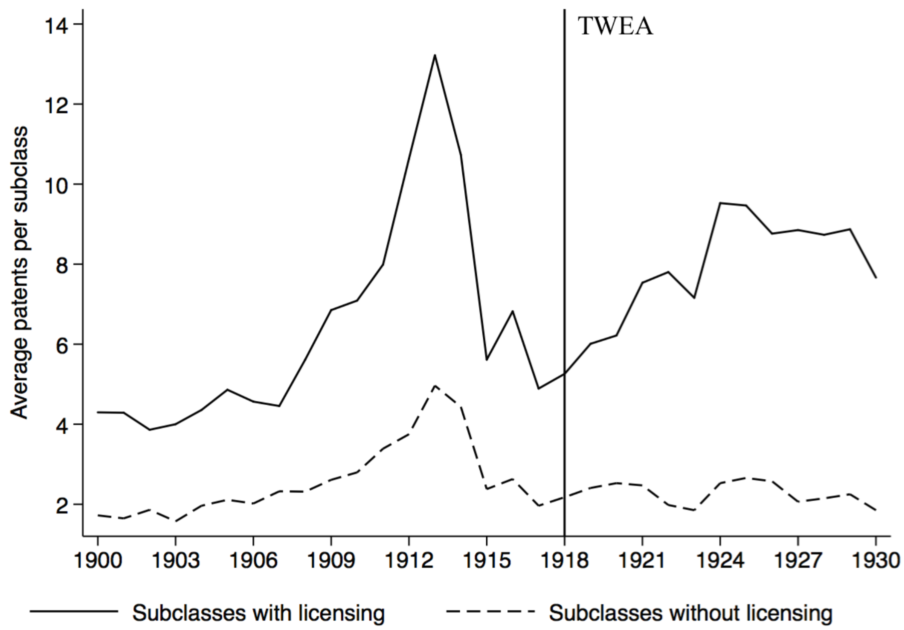
FIGURE A3 – RENEWAL DATA FOR GERMAN PATENTS 1900-1930



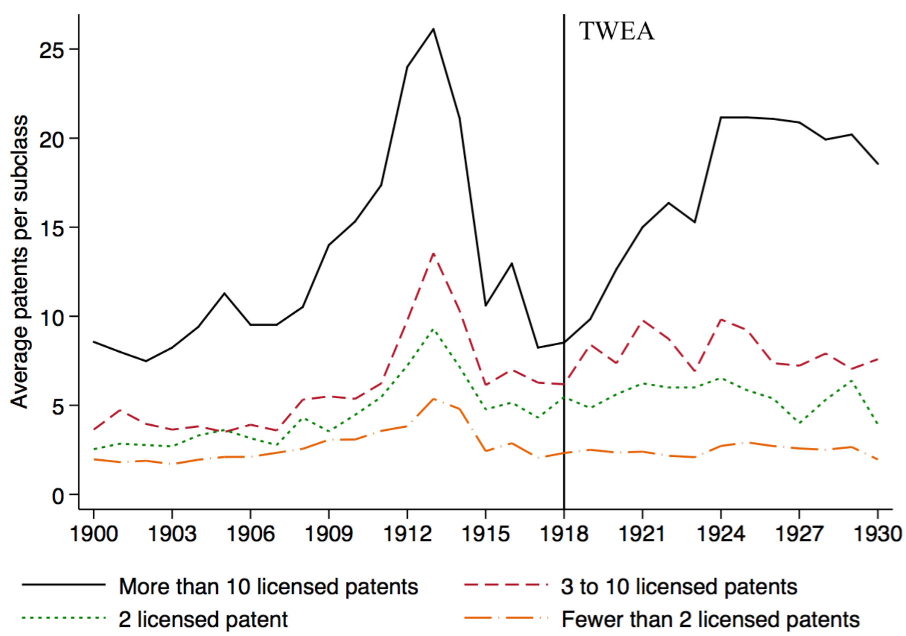
Notes: *Years renewed* are measured at the last year in which a patentee pays the renewal fee that the GPO required to keep a patent active. Fifty percent of all patents were renewed for 5 years or more; the average patent was renewed for 6 years. Data include the complete renewal history of 79,591 German patents for chemical inventions with application years between 1900 and 1930. We have collected these data from German-language copies of the *Annual Reports* of the GPO between 1901 and 1942.

FIGURE A4 – PATENTS THAT WERE RENEWED FOR FIVE YEARS OR MORE

PANEL A – SUBCLASSES WITH AND WITHOUT LICENSED PATENTS

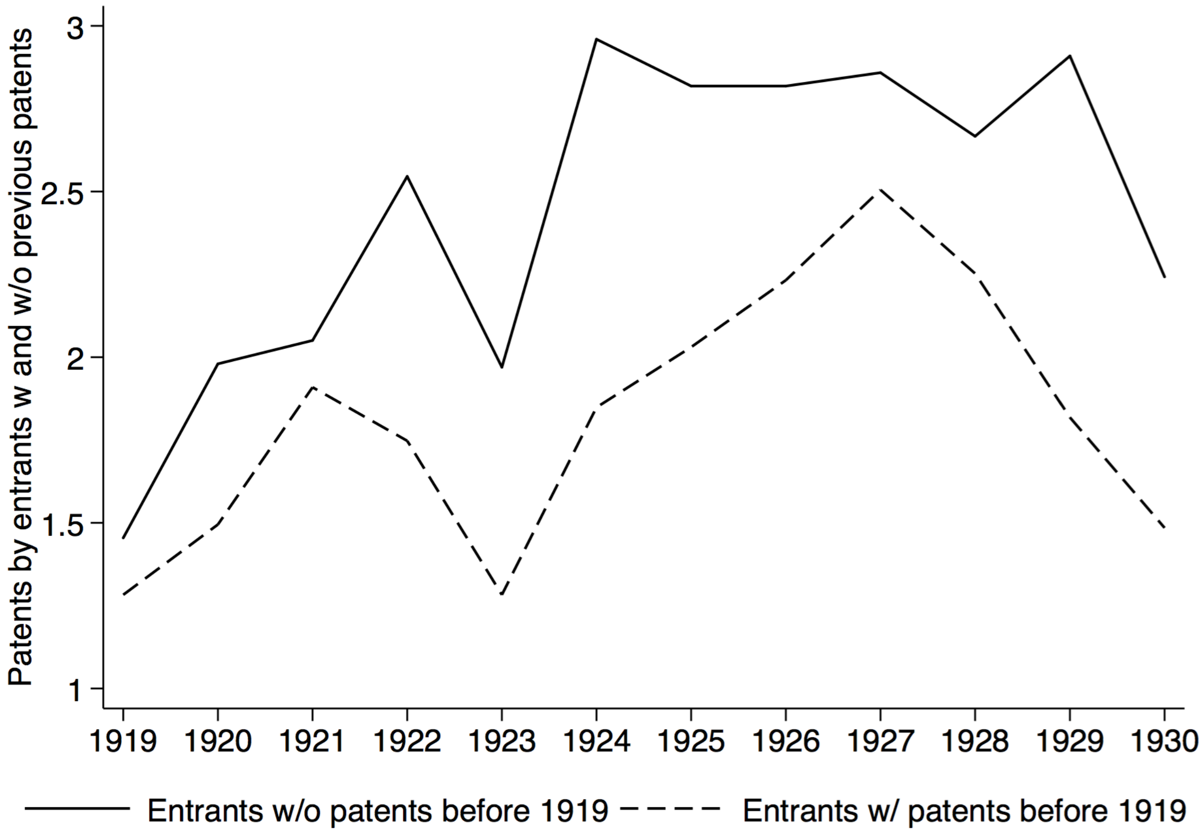


PANEL B – QUARTILES OF THE DISTRIBUTION OF LICENSED PATENTS



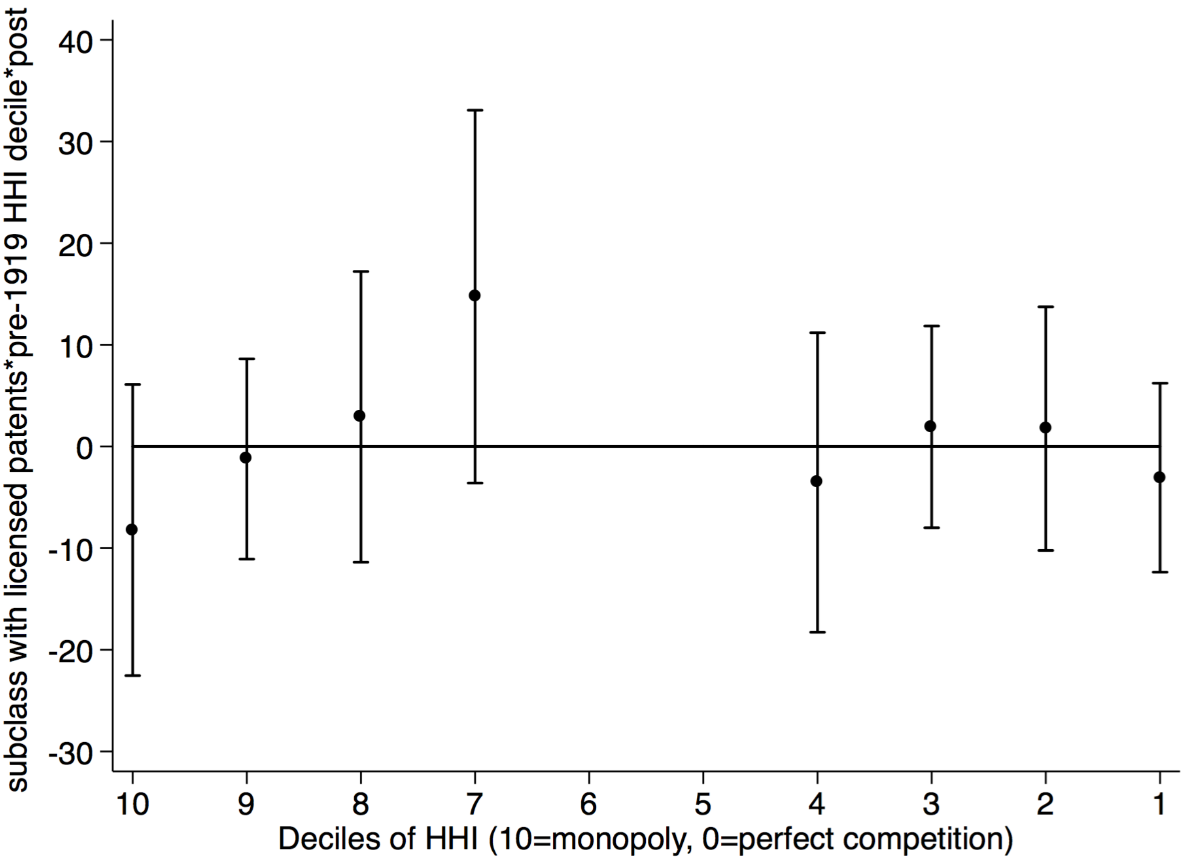
Notes: Data include 30,017 GPO patents by German inventors that were renewed for 5 years with application between January 1, 1900 and December 31, 1930. We have constructed these data by reconstructing the renewal history of all GPO patents by German inventors from the GPO's Annual Report (*Verzeichnis der im Vorjahre erteilten Patente*) between 1900 and 1942. 101 *subclasses with licensing* each include at least one US patent by a German firm was licensed under the TWEA; 111 *other subclasses without licensing* include no licensed patents.

FIGURE A5 – PATENTS BY ENTRANTS WITH AND WITHOUT PREVIOUS PATENTS



Notes: Entrants without previous patents before 1919 are patents by new entrants in subclasses with licensing without patents before 1919. This includes patents by firms that never patented before and by firms that have patented only after 1919 in other technology fields. *Entrants with previous patents before 1919* are patents by new entrants in subclasses with licensing that patented in other chemical subclasses before 1919.

FIGURE A6 – ESTIMATED EFFECT OF COMPULSORY LICENSING ON COMPETITION



Notes: The figure plots estimates of the interaction *subclass with licensed patents*$_c$ • *pre-1919 HHI decile*$_d$ • *post*$_t$ for the baseline specification. The variable *subclass with licensed patents* is equals one for 101 subclasses of German patents, in which at least one German-owned US patents became subject to compulsory licensing in 1918. The indicator variable *post* equals 1 for all years after 1918; *pre-1919 HHI decile*$_d$ is a set of indicators for the deciles of the pre-1919 distribution of the HHI, which measures pre-TWEA competition in patenting. The 5th and 6th decile are omitted; bars present the 95th percent confidence intervals reported. Data include all 79,591 applications for patents on chemical inventions between 1900 and 1930.

TABLE A4 – OLS, DEPENDENT VARIABLE IS PATENTS PER SUBCLASS AND YEAR EXCLUDING WAR YEARS 1915-1918

	(1)	(2)	(3)	(4)	(5)	(6)
Subclass with licensed patents * post	3.221***	5.362***	5.668***	5.494***		
	(0.982)	(1.533)	(1.436)	(1.421)		
Licensed patents * post					0.192***	0.455***
					(0.070)	(0.122)
Licensed patents^2 * post					-0.001***	-0.001***
					(0.000)	(0.000)
Patents by U.S. inventors	0.969***		0.762***	0.966***	0.924***	0.717***
	(0.151)		(0.165)	(0.151)	(0.154)	(0.158)
Patents by other foreign	1.461***		1.421***	1.453***	1.359***	1.236***
	(0.227)		(0.265)	(0.226)	(0.158)	(0.162)
Standard errors (in parentheses) are clustered at the level of subclasses, *** p<0.01, ** p<0.05, * p<0.1						
Mean in subclasses with licensing 1900-18	10.77	10.77	10.77	10.77	10.77	10.77
Subclass-specific pre-trends	No	No	Yes	No	No	Yes
Pre-trend for subclasses with licensing	No	No	No	Yes	No	No
Subclass fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
N	5,724	5,724	5,724	5,724	5,724	5,724

Notes: Data include all 71,963 applications for patents on chemical inventions between 1900 and 1930, excluding the war years 1915 to 1918. *Subclass with licensed patents* is an indicator variable that equals one for 101 German subclasses, in which at least one US patents became subject to compulsory licensing. The indicator variable *post* equals 1 for all years after 1918. The variable *licensed patents* measures the number of patents that became subject to licensing. *Patents by US inventors* controls for the number of patents that the GPO issued to residents of the United States in subclass *c* and year *t*; *patents by other foreign* controls for the number of patents that the GPO issued to residents of other foreign countries.

TABLE A5 – TOP TEN GPO SUBCLASSES BY NUMBER OF LICENSED GERMAN-OWNED US PATENTS

Class number	Class name	Confiscated patents	Licensed patents	German patents per year	
				1900-1918	1919-1930
22a	Azo-dyes	863	436	28.79	24.17
12o	Hydrocarbons	621	242	88.84	173.42
12i	Metalloids	349	146	52.05	103.25
12q	Aminophenols	289	110	49.68	82.50
12k	Ammonia	177	108	18.95	23.50
8m	Dyeing	258	105	23.47	27.50
85b	Water purification	73	54	7.89	8.42
8n	Calico printing	151	52	9.11	8.50
8k	Mercerizing	159	49	9.47	12.17
22g	Inks	126	36	12.42	28.83

Notes: *Confiscated patents* measures the number of patents that were seized by U.S. authorities under the TWEA and made available for licensing. *Licensed patents* counts German-owned US patents that were licensed under the TWEA. *German patents per year* counts the number of German patents by German inventors, measured in their application year.

TABLE A6 – ITT, DEPENDENT VARIABLE IS PATENTS RENEWED FOR AT LEAST 5 YEARS PER SUBCLASS AND YEAR

	(1)	(2)	(3)	(4)	(5)	(6)
Subclass with confiscated patents * post	0.833**	1.493***	2.270***	2.205***		
	(0.400)	(0.514)	(0.659)	(0.654)		
Confiscated patents * post					0.033***	0.074***
					(0.011)	(0.020)
Confiscated patents^2 * post					-0.000**	-0.000***
					(0.000)	(0.000)
Patents by U.S. inventors	0.835***		0.712***	0.830***	0.759***	0.626***
	(0.150)		(0.164)	(0.150)	(0.135)	(0.139)
Patents by other foreign	1.204***		1.147***	1.200***	1.120***	1.059***
	(0.187)		(0.208)	(0.187)	(0.151)	(0.162)
Standard errors (in parentheses) are clustered at the level of subclasses, *** p<0.01, ** p<0.05, * p<0.1						
Mean in subclasses with licensing 1900-18	6.28	6.28	6.28	6.28	6.28	6.28
Subclass-specific pre-trends	No	No	Yes	No	No	Yes
Pre-trend for subclasses with confiscated patents	No	No	No	Yes	No	No
Subclass fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
N	6,572	6,572	6,572	6,572	6,572	6,572

Notes: Data include all 39,682 applications for patents on chemical inventions between 1900 and 1930 that were renewed for a minimum of 5 years. Data on renewal decisions come from archival records of renewed patents from the *Annual Reports* of the German patent office between 1901 and 1942. *Subclass with confiscated patents* is an indicator variable that equals 1 for 171 German subclasses in which at least one U.S. patents was confiscated after the TWEA. The indicator variable *post* equals 1 for all years after 1918. *Confiscated patents* measures the number of patents that were seized by U.S. authorities after the Trading With the Enemy Act in subclass *c*. *Patents by U.S. inventors* controls for the number of patents that the German Patent Office issued to residents of the United States in subclass *c* and year *t*; *patents by other foreign* controls for the number of patents that the German Patent Office issued to residents of other foreign countries.

TABLE A7 – FIRMS THAT MERGED TO CREATE *IG FARBEN*: EXPOSURE TO LICENSING AND CHANGES IN PATENTING

	Licensed patents		Patents per subclass and year							
			All patents				Patents renewed ≥5 years			
			Subclasses with licensed patents		Other Subclasses		Subclasses with licensed patents		Other subclasses	
	All subclasses	Azo-dyes (22a)	1900-1924	1925-1930	1900-1924	1925-1930	1900-1924	1925-1930	1900-1924	1925-1930
Bayer	551	258	1.19	4.16	0.22	0.46	0.97	2.51	0.23	0.34
			(3.66)	(10.02)	(0.83)	(0.98)	(3.08)	(5.73)	(0.78)	(0.70)
BASF	308	82	0.99	3.08	0.26	0.45	0.78	1.94	0.25	0.30
			(2.70)	(5.93)	(0.94)	(1.12)	(2.21)	(3.71)	(0.85)	(0.65)
Hoechst	104	34	1.12	3.01	0.44	0.78	0.77	1.57	0.44	0.53
			(3.32)	(6.67)	(1.78)	(2.24)	(2.36)	(3.55)	(1.56)	(1.36)
Griesheim- Elektron	57	12	0.33	1.39	0.09	0.35	0.27	0.95	0.09	0.21
			(1.10)	(2.82)	(0.40)	(1.04)	(0.90)	(1.74)	(0.43)	(0.73)
AGFA	38	26	0.42	1.62	0.18	0.14	0.26	0.86	0.15	0.05
			(1.31)	(4.05)	(0.78)	(0.35)	(0.84)	(2.01)	(0.69)	(0.12)
Weiler Ter Meer	1	1	0.07	0.28	0.02	0.00	0.03	0.13	0.02	0.00
			(0.40)	(1.10)	(0.16)	(0.00)	(0.19)	(0.57)	(0.14)	(0.00)

Notes: Data include all German patents on chemical inventions by the six firms that merged into *IG Farben* - *AGFA, Bayer, BASF, Hoechst, Griesheim-Elektron,* and *Chemische Fabrik vorm. Weiler Ter Meer* - with application years between 1900 and 1930. *Licensed patents* are German-owned patents, which the US Alien Property Custodian made available for licensing after the 1918 US TWEA. *Subclasses with licensed patents* denotes 101 out of 212 GPO chemical subclasses, in which at least 1 US patents became subject to compulsory licensing. Standard deviation in parentheses.

TABLE A8 – EXCLUDING DATA AFTER 1924, PATENTS RENEWED FOR AT LEAST 5 YEARS PER FIRM, SUBCLASS, AND YEAR

	(1)	(2)	(3)	(4)
Subclass w licensed patents * firm w licensed patents * post	0.130**	0.125**	0.164	0.130**
	(0.052)	(0.052)	(0.000)	(0.052)
Subclass w licensed patents * post	0.014**	0.028***	0.015	0.014**
	(0.006)	(0.007)	(0.000)	(0.006)
Patents by U.S. inventors	0.002		0.001	0.002*
	(0.001)		(0.000)	(0.001)
Patents by other foreign	0.003***		0.003	0.003***
	(0.001)		(0.000)	(0.001)
Patents by individuals	0.003***		0.003	0.003***
	(0.000)		(0.000)	(0.000)
Standard errors (in parentheses) are clustered at the level of firms, *** p<0.01, ** p<0.05, * p<0.1				
Mean for firms with licensed patents, 1900-18	0.46	0.46	0.46	0.46
Subclass-specific pre-trends	No	No	Yes	No
Pre-trend for firms with licensing	No	No	No	Yes
Subclass fixed effects	Yes	Yes	Yes	Yes
Firm fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes
N (Subclass-firm-year)	132,425	132,425	132,425	132,425

Notes: Regressions also include *firms w licensed patents * post, licensed patents * firms w licensed patents*, and *subclass w licensed patents * firms w licensed patents.* Data include GPO patents for chemicals with application years between 1900 and 1924 that were renewed for a minimum of 5 years. Data on renewal decisions come from the *Annual Reports* of the GPO between 1901 and 1942. *Firm w licensed patents* equals 1 for 50 German firms that owned at least 1 US patents that became subject to compulsory licensing. The indicator variable *post* equals 1 for years after 1918. *Subclass w licensed patents* is an indicator variable that equals 1 for 101 German subclasses, in which at least 1 US patents became subject to compulsory licensing. *Patents by US inventors* controls for GPO patents to US residents in subclass *c* and year *t*; *patents by other foreign* and *patents by individual inventors* control for GPO patents to other foreign and individual (non-firm) inventors, respectively.