# Inventors and Firm Innovation:

## Evidence from the U.S. World War I Draft

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**Abstract**

I investigate the impact of individual inventors on a firm's innovation activity using the WWI draft as an exogenous shock to the labor supply of inventors. I find that the loss of inventors working with a firm decreases the firm's inventions, the loss of other inventors in the same geographical location does not affect the firm's inventions, and the loss of inventors in the same industry increases the firm's inventions. Industry-level data indicates that the loss of inventors attracts new inventors and firms to the industry. New ideas and generations are generated, given a vacancy in the space of ideas.

*Keywords:* Inventor, firm innovation, WWI

*JEL classification:* J24, N42, O31

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# I Introduction

The interest in knowledge spillovers goes back to at least Bernard in the twelfth century, who noted, "We are like dwarfs on the shoulders of giants, and thus, we are able to see more and farther than the latter." This same sentiment was echoed in 1675 by Newton. While each generation creates knowledge that is, at least in part, inspired by the ideas of previous thinkers, new ideas might also be developed as a response to the "vacuum" that results when those who have dominated the field disappear. This vacuum phenomenon was first formally suggested by Max Planck in 1950, and interest in knowledge creation and spillovers has persisted until today. However, we still know little about the process and dynamics of knowledge production (Jones, 2005).

The study of knowledge production is difficult in that firms play a foundational role in creating new ideas and inventions, whereas most of the natural experiments documented in the literature are conducted and read by individual knowledge producers, such as inventors and academic scientists. Firms account for 82 to 85 percent of U.S. patents between 2006 and 2016 (National Science Board, 2018), and these patents result in ripple effects on economy-wide innovation. To develop innovations, firms typically hire or work with highly skilled workers, such as inventors, who hold patents. These workers face challenges to their labor supply, including the possibility of migration, health shocks, government conscription, etc.

While an inventor's human capital is presumably the most important input to a firm's knowledge production function, few studies exist on how a labor supply of inventors propagates into a firm's innovation activity. As a result, research has yet to address the interactions between inventors and firm innovation. We, therefore, know little about which firms produce new knowledge that generates spillovers or which firms depend heavily on knowledge spillovers to produce new innovations. In this paper, I introduce new matched firm–inventor data and use the WWI draft to provide the first causal evidence of how supply shocks of inventors affect firm-level innovation. Specifically, I investigate the firm's knowledge production measured by patent applications when the firm exogenously loses inventors because of the draft and military service.

The potential effects of the loss of inventors on firm innovation are not a priori, obviously because inventors do not necessarily work for a single firm. For example, they can work alone as entrepreneurs, in a team with other individuals, or with several firms. The loss of inventors who work directly with a firm or outside the firm, such as geographically close inventors and inventors in the same industry who generate knowledge spillovers, could decrease a firm's overall invention production. However, inventors do not always produce knowledge spillovers. In fact, inventors may have negative competition effects on a firm's innovation activity. The loss of inventors who compete with a firm as entrepreneurs or who work with rivals of the firm could increase the firm's invention production.

To investigate the consequences of the loss of inventors on a firm's innovation activity through a variety of mechanisms, I consider the three conceptually different types of inventors: (1) team members working directly with the firm; (2) geographically close inventors; and (3) inventors working on similar topics to those a firm is working on (Borjas and Doran, 2015a). I introduce a new database of patent applications matched to firm and individual inventor characteristics. To estimate the causal effects of inventors on the dynamics of a firm's innovation activity, I use a documented large labor supply shock that affected some inventors but not others: the U.S. draft during WWI. Given the specificity of the age groups affected by the draft, some pools of inventors were heavily depleted during the war, while other pools were left relatively unaffected. These differential effects occurred across all three types of inventors. As a result, the data set I use in this study could be used to differentiate among the separate effects of the loss of inventors within a firm's team, within a geographic location, or within an area in the space of ideas on a firm's innovation production.

I construct a unique data set by matching records among the patent database, WWI records, and the 1920 U.S. Census. The linked data set contains information on the number of patent applications per year, WWI draft registrations, WWI military service records, geographic locations, and inventors' characteristics from the complete count census. Using variation in the proportion of inventors of draftable age, I use a difference-in-differences setup to identify the impact of the loss of inventors on a firm's invention. Specifically, I estimate the innovation rates of firms that are more versus less likely to lose inventors in a firm's team, in the same county, or in the same industry because of the WWI draft and military service between 1917 and 1918. I provide evidence of the validity of the identification strategy from a placebo experiment demonstrating that inventors of undraftable age are unlikely to impact a firm's invention production.

I find evidence that the effect of supply shocks to inventors on firm innovation depends heavily on both the space in which the shock takes place and how close the firm is to the knowledge frontier. The loss of inventors working with the firm as team members decreases the firm's inventions, but the loss of inventors in the same geographical county does not significantly affect the firm's inventions. In fact, the loss of inventors outside the firm yet working in the same industry actually increases the firm's inventions. In particular, a 10 percent decrease in inventor team members within a firm decreases the number of patent applications assigned to the firm by 12 percent per year. In contrast, a 10 percent decrease in inventors working in the same industry increases patents assigned to that firm by 8 percent. This increase in patents is driven by firms that are highly innovative prior to the WWI draft, while less innovative firms experience a decrease in innovation rates in response to the loss of inventors in the space of ideas.

Taken together, this evidence suggests that knowledge spillovers have different effects within a firm than they do among firms. Within a firm, knowledge spillovers are powerful enough to negate any diminishing marginal returns to the firm's pool of inventors. Among firms, knowledge spillovers primarily work through the transfer of ideas from highly innovative firms to their less innovative peers. Among highly innovative firms already at the knowledge frontier themselves, knowledge spillovers in the space of ideas are not a substantial determinant of knowledge production. Highly innovative firms fill the void created by the loss of inventors in the space of ideas.

Furthermore, I disaggregate the effects of losing inventors by the quality of inventors. I find that inventor quality is an important determinant of firm innovation and that high-quality inventors are not replaceable for a firm's knowledge production. Within a firm, highly innovative knowledge producers disproportionately affect the invention production of the firm as a whole. The quality of inventors explains how the overall effect of the loss of inventors within the same geographical county is cancelled out. The law of diminishing marginal returns by low-quality inventors offsets knowledge spillovers generated by high-quality inventors.

I investigate the mechanism by which the loss of inventors in the industry affects the industry's innovation. Industry-level analysis indicates that the loss of inventors helps attract new inventors and firms to the industry. Because of these new entrants, the industry's innovation activity does not decrease in response to the loss of inventors in the industry.

To my knowledge, this paper is the first to provide empirical evidence of the impact of inventors on firm innovation using an exogenous shock to the labor supply of inventors. The results presented in this paper contribute to two bodies of literature. First, these results add to a growing number of studies that explore how a supply shock of knowledge producers affects knowledge spillovers. The results here suggest that researchers who examine the process of knowledge production by individuals but ignore the roles of firms in that process could be missing an important source of knowledge creation and spillovers that may have implications for economy-wide innovations. The existing literature on supply shocks and knowledge spillovers is motivated by different theoretical perspectives. One view considers human capital externalities in which the creation of new ideas generates positive externalities. This provides evidence that losing peers has a negative impact on knowledge creation.[1] Other studies have demonstrated that the inflow of knowledge producers creates positive externalities.[2] This suggests that knowledge producers have a positive impact on one another's knowledge production.

Another perspective follows the law of diminishing marginal returns and negative competitive effects in which the loss of peers has a positive impact on the rate of knowledge production. This hypothesis suggests that knowledge producers take advantage of the de-

[1]For example, Waldinger (2010) finds that PhD students suffer after superstar scientists who trained them emigrate. Azoulay, Graff Zivin, and Wang (2010); Jaravel, Petkova, and Bell (2018) provide evidence that the loss of knowledge producers causes a decline in the productivity of collaborators. Iaria, Schwarz, and Waldinger (2018) examine the impact of the collapse of international scientific cooperation and find a decrease in new knowledge and technology. Examples of collaboration would include Wuchty, Jones, and Uzzi (2007); Jones (2009).

[2]For example, Moser, Voena, and Waldinger (2014) document knowledge spillovers in which immigrant researchers attract new researchers to their fields and encourage innovation. Borjas, Doran, and Shen (2018) find that the influx of Chinese students into the United States increases the output of Chinese American "advisors who advise the Chinese students." Bernstein, Diamond, McQuade, and Pousada (2019) find that immigrant collaborators create strong positive spillovers. Doran, Gelber, and Isen (2016) find that firm-level invention does not increase when a firm receives high-skilled immigrants. Examples of collaboration would include Kerr, Kerr, Ozden, and Parsons (2016); Kerr and Kerr (2018). Further examples of knowledge spillovers in specific geographic locations include Jaffe, Trajtenberg, and Henderson (1993); Keller (2002); Thompson and Fox-Kean (2005); Thompson (2006); Singh (2005); Ellison, Glaeser, and Kerr (2010); Belenzon and Schankerman (2013); Moretti (2019).

crease in competition within their field[3] and thus have a negative impact on one another's knowledge production. In this paper, I provide evidence that addresses both human capital externalities and the presence of diminishing returns by distinguishing the separate effects of the loss of inventors within a firm's team, within a geographic location, and within a particular space of ideas. This paper, therefore, aims to investigate the process and dynamics of the firm's knowledge production through such a variety of supply shocks of inventors instead of the effect on individuals that most previous studies have examined.

Second, this paper builds on a rich body of literature that examines the determinants of firm innovation. Despite the importance of human capital in firm innovation, we know little about how a labor supply of inventors affects a firm's innovation activity. One group of early studies of this topic explored a relationship between R&D investment and firm innovation,[4] while another group of papers related competition to firm innovation following Schumpeter (1942).[5] Recent studies investigate various determinants of firm innovation other than R&D.[6] Acemoglu (2010) developed a theoretical model that explains how labor affects technological advances, but it is an open empirical question of how inventors' human capital affects a firm's knowledge production. This paper, therefore, advances our understanding of how knowledge is generated by connecting the literature that addresses knowledge spillovers with that of firm innovation.

I begin by describing the context of the WWI draft in Section II. I use Section III to provide data and Section IV to present empirical strategies. I report the results in Section V and investigate the channels through which supply shocks affect firm-level innovation in Section VI. I provide a conclusion to the study in Section VII.

[3]For example, Waldinger (2012) finds that researchers who were left behind after their colleagues emigrated did not experience a decrease in productivity. Similarly, Borjas and Doran (2012, 2015b) examine the output of American mathematicians when Soviet mathematicians immigrated into the United States. These authors find that American mathematicians in fields that received an influx of Soviet mathematicians experienced a decrease in productivity and moved away from such fields. Furthermore, Azoulay, Fons-Rosen, and Graff Zivin (2019) argue that the loss of knowledge producers provides an opportunity for non-collaborators in a field.

[4]See, for example, Acs and Audretsch (1988, 1987); Acs, Audretsch, and Feldman (1994).

[5]For example, see Gilbert (2006); Cohen (2010).

[6]For example, Autor, Dorn, Hanson, Pisano, and Shu (2019) quantify how foreign competition influences domestic innovation. Aghion, Bergeaud, Lequien, and Melitz (2018) measure the effect of export shocks on innovation. Examples include Akcigit and Kerr (2018); Atkeson and Burstein (2018); Acemoglu, Akcigit, Alp, Bloom, and Kerr (2018).

# II Historical Context

World War I began in Europe on July 28, 1914, with the United States entering the war on April 6, 1917. Only 73,000 volunteers enlisted in response to an immediate call for volunteers, a number far short of the goal of one million in the first six weeks after the call. The Selective Service Act, which manages conscription in the United States, was enacted one month after this initial call for volunteers. In 1917 and 1918, all men between the ages of 18 and 45 were required to register. Approximately 24 million men, nearly 98 percent of the population of men aged 18 to 45, completed draft registration cards during three rounds of registrations. As a result of three draft lotteries, about 2.8 million men served in the military from 1917 to 1918. Figure A.1 shows how many persons were engaged in military service over time (Kendrick, 1961).[7] The labor force in the public sector thus significantly increased at the time of the WWI draft (Figure B.1). Military expenditures in Figure B.2 also surged when the United States entered the war, with one fifth of U.S. resources spent on the war effort (Rockoff, 2004).

Not all men who had registered for the draft during WWI served in the military. Furthermore, not all men who had served in the military registered for the draft since some men were already serving during registration. Table A.1 shows the number of men who registered, were drafted, and served, as well as information about their status as patent holders (U.S. Provost Marshal General, 1919). Specifically, about 10 million men aged 21 to 30 registered in the first draft registration on June 5, 1917, and about one million men who had turned 21 registered in the second draft registration on June 5, 1918. The third registration on September 12, 1918, was intended for all remaining men aged 18 to 45 who had not registered in the first or second registration.

Because WWI ended on November 11, 1918, the majority of men who had been drafted and served through draft lotteries came from the first and second registrations. Fewer than 200,000 men were inducted from the third registration despite about 13 million men having registered in the third round. Each registrant provided his name, age, address, birth date, citizenship status, and occupation on his draft registration card (Figure A.2).

[7] See the online Appendix (https://sites.google.com/site/chungeunyoon).

Three draft lotteries randomly determined the draft order for registrants if they did not provide a valid excuse as to why they were not able to serve in the military. Most of the registrants who had been drafted eventually served in the military unless they claimed for exemption and their claim was granted. Fewer than 350,000 men who had been selected were successful in gaining exemption.

The first national draft lottery was held on July 20, 2017. Secretary of War Newton D. Baker drew 258, the first draft number in the lottery (Figure 1). Each registrant in every local draft board throughout the country whose number was 258 was given an order number of 1. A total of 4,648 local draft boards managed draft registrations and conscription under the Selective Service Act. Thus, more than 4,000 men whose registration number was 258 were first drafted from each local board. This process was repeated until 10,500 numbers were drawn. According to this order number, all registrants were required to appear before the local board for a physical examination or to claim exemption. The numbers in the second and third registrations were drawn in the same manner from the second and third draft lotteries, respectively.

The fact that different age groups were drafted during different times provides a possible identification strategy based on which portion of inventors in a firm was in different age categories. In the next section, I describe how the data could be used to identify the age of inventors within particular firms who served in the military.

# III Data and Matching

My empirical analysis examines how the number of patent applications from firms is affected by the negative inventor supply shocks from the WWI draft. To investigate this, I create a new matched firm–inventor data set using a PATSTAT database provided by European Patent Office (2017) that contains the characteristics of each patent application, such as the inventor's full name and year of application. This database draws from more than 100 patent documents from 40 patent authorities, including the United States Patent and Trademark Office (USPTO). The PATSTAT database also contains information on the field (International Patent Classification or IPC) of each patent application. To construct firm-level patent data, I use patents by "company" in a type attribute of inventors in the PATSTAT database. The data allows me to identify when individual inventors file a patent application together with which firms.

To determine how innovation rates are impacted when firms lose geographically close inventors, I need to know where inventors lived when the WWI draft had occurred and where the firms were located. I use data from Doran and Yoon (2019), in which patent data is merged into census data at the individual level. A fuzzy matching procedure performs a match between the patent database and the complete 1920 U.S. Census with the full names of individuals. In the census, 43 percent of the U.S. population had unique first name, middle name, and last name combinations. To increase the probability that the fuzzy matching procedure is precise, I only consider the population with unique names between the ages of 18 and 80 (Doran and Yoon, 2019) as well as patents matched between the years 1910 and 1918 in regression specifications, thus reducing the probability of the results being caused by those who died or migrated. Because a person could move geographically, the identifying assumption when measuring the supply shock within a geographic space is that a person with a unique name observed in 1919 from the complete count of the 1920 census lived at the same place between 1917 and 1918 when the WWI draft had occurred. As a proxy for a firm's location, I conduct a matching procedure between the PATSTAT database and the HistPat database (Petralia et al., 2016), which provides the geography of patents by the USPTO from 1790 to 1975. I calculate the location of each firm by the most frequently reported locations in the HistPat database.

The data linked to the census provides the inventors' ages and locations. By constructing this novel linked data, I thus identify which firms worked with which inventors at which ages, where the firms and inventors were located, and when and in what fields the inventors filed patent applications.

I use the platform FamilySearch, which publicly shares a large collection of historical records, to collect draft registration and veteran service records. In particular, I collect information recorded on WWI draft registration cards from the three registrations rounds. Figure A.2 shows an example of the draft registration card from the first registration. Though the information in each registration was slightly different, each registrant provided his full name, age in years, home address, date of birth, citizenship status, and occupation or employer's name on his draft registration card. Information on the full names and birth dates is digitized and publicly available at FamilySearch.org.[8]

I collect information by conducting a matching procedure on the web. I first create a donor pool of draftable inventors who were active during the WWI draft. This pool is limited to inventors who were not foreign-born, who were 18 to 45 years old between 1917 and 1918, and who had any patent applications before 1917. I conduct a match between their full names and birth years in the patent database merged into the 1920 census and those in WWI draft registration cards on FamilySearch (2019a). I find that about 96 percent of the inventors between the ages of 18 and 45 were registered, a registration rate close to the overall reported rate of 98 percent. I also collect WWI veteran records from FamilySearch (2019b), following the same procedure. FamilySearch provides information on the full names and birth years of veterans who served during WWI.

Draft registration differs from draft and service in the military. Men who registered could voluntarily serve even though they were not drafted. Furthermore, men who were drafted could evade the draft or fail the physical examination. In Table A.1, I report the populations within each of these categories. Since draft records were not available, three different groups (registered and served, registered but did not serve, and neither registered nor served) could be identified after a matching procedure between the patent database and WWI draft registration and service records. I use this data to create supply shocks of inventors who served in the military. The merged data also allows me to measure the effects of inventors who did not serve on the innovation rates of other individual inventors, specifically those who registered but did not serve or who neither registered nor served while their peers served.

Table 1 provides descriptive statistics for the firm panel data used in the empirical analysis. The sample consists of firms that had at least one patent application prior to the WWI draft and had no patent applications belonging to the arms industry, where weapons, ammunition, or explosives are manufactured. Additionally, war-related patents are not counted

[8]Ancestry.com, another large platform containing genealogical and historical records, also provides more complete sources but prohibits automatic access tools, and it is not publicly available.

as the outcome of the number of patent applications. Specifically, I use the IPC in the patent database to identify which patents belong to the arms industry.[9] Some characteristics of individual firms could change how a particular firm experienced the effects of WWI on innovation rates. For example, firms that produced weapons during WWI could have experienced a large increase in their output and thereby an increase in their inventions when WWI began or when the United States entered the war. To address this issue, I use the sample of firms not related to the arms industry and the outcome of patents not related to the same industry.

Firms significantly experienced a decrease in their innovation rates during the WWI draft. Consistent with the sample, USPTO administrative data shows a sharp decline during the WWI draft in patent applications (Figure B.3). This decrease could be due to the fact that the nation's resources were devoted to the war effort and that 2.8 million men, including inventors, were induced into the military during this time. The number of inventors represents the number of inventors per firm in each of the following three distinct categories between 1910 and 1918: inventors in a collaboration space who filed a patent application together with a firm, inventors in a geographic space who lived in a county where a firm was located, and inventors in a space of ideas who filed a patent application classified in a particular field where a firm had a patent.

In the next section, I outline empirical strategies that deal with the possibility of endogenous military service by inventors and the potential confounding effects of WWI.

# IV Identification

## 4.1 Estimating effects

I begin the empirical analysis by measuring the shocks to the labor supply, disaggregated by the three types of inventors. Specifically, I define the supply shocks that firms encountered as falling into three distinct categories: the network of collaboration, the space of geography, and the space of ideas.

[9] The following IPC codes are relevant for the arms industry: F41A, F41B, F41C, F41F, F41G, F41H, F41J, F42B, F42C, F42D, B63G, C06B, and G21J.

I first calculate the supply shock of team members who worked for a firm or collaborated with the firm in collaboration space. Firm $j$ may have had team members who had any patent applications with firm $j$ before WWI. Some of team members of firm $j$ were drafted and inducted into the military, and some of them did not serve. I use the linked patent data that provides information on the service records. In particular, let $P_{jCs}$ be the number of pre-WWI patents between 1910 and 1916 by inventors who worked with firm $j$ and served in the military, and let $P_{jC}$ be the number of pre-WWI patents by inventors who worked with firm $j$. The collaboration-specific service rate is then defined as

$$S_{jC} = \frac{P_{jCs}}{P_{jC}} \tag{1}$$

The variable $S_{jC}$ measures the supply shock experienced by firm $j$ when they lost their network of collaborators because of the WWI draft. The supply shock in collaboration space is used to measure the direct impact of an inventor's human capital on a firm's patenting capacity. The share of team members who served in the military is weighted by the number of pre-WWI patents assigned to inventors. This is because the effect of the loss of one member in a firm is not always the same. The shock depends on inventor productivity. I assume that no supply shock exists if the firm did not work with any individual inventors before the shock (i.e., the supply shock has a value of zero if the denominator is zero).

To measure the supply shock in geographic space at the firm level, I need to identify the geographic location of firm $j$ and the associated inventors. I track the locations of firms at the county level by using information on the geography of patents from HistPat that covers patents by the USPTO from 1790 to 1975. To identify the locations of the inventors, I use the information on the 1920 census merged into the patent data. I assume a person observed in the 1920 census lived in the same geographic location between 1917 and 1918.

Then let $P_{Gs}$ be the number of pre-WWI patents by inventors who served and lived in county $G$, where firm $j$ is located, and let $P_G$ be the number of pre-WWI patents by inventors in county $G$. The geographic-specific service rate at the firm level is then defined by

$$S_{jG} = \frac{P_{Gs}}{P_G} \tag{2}$$

The variable $S_{jG}$ measures the supply shock that firm $j$, located in county $G$, faced during the WWI draft. Figure 2 shows the degree of the supply shock in each U.S. county.

The supply shock in the space of ideas is measured using information on the IPC, available in the PATSTAT database, which specifies the field of each patent application. I assign each of the patent applications to a weighted set of 84 patent classifications (Table B.1). Let $patent_{jf}$ be the number of pre-WWI patents in field $f$ by firm $j$ and $patent_j$ be the total number of pre-WWI patents by firm $j$. Then let $P_{fs}$ be the number of pre-WWI patents in field $f$ by inventors who served, and let $P_f$ be the number of pre-WWI patents in field $f$ by all inventors. The field-specific service rate, calculated by the field composition of firm $j$, is defined as

$$S_{jF} = \sum_f \frac{patent_{jf}}{patent_j} \frac{P_{fs}}{P_f} \tag{3}$$

The variable $S_{jF}$ measures the supply shock that firm $j$ encountered when they lost inventors in a similar field.

Using the measure of the supply shocks and panel data set of firm-level outcomes, I investigate the effects of the inventor supply shocks on firm outcomes with difference-in-differences specifications in the following regression model:

$$Y_{jt} = \beta_1(S_{jC} \times T_t) + \beta_2(S_{jG} \times T_t) + \beta_3(S_{jF} \times T_t) + \theta X_{jt} + \gamma_j + \delta_{st} + \epsilon_{jt} \tag{4}$$

where $Y_{jt}$ is the outcome of firm $j$ in year $t$ such as the number of patents; $S_{jC}, S_{jG}$, and $S_{jF}$ are firm-specific supply shocks in each of the spaces, respectively; and $T_t$ is a dummy variable for the years 1917 and 1918. I include the quartic of years of experience of firm $j$ in year $t$ ($X_{jt}$), firm fixed effects ($\gamma_j$), and state-by-year fixed effects ($\delta_{st}$) that thus control for state-specific yearly shocks. I define the years of experience of firm $j$ as the years after firm $j$ had its first patent application. The coefficients of interest are $\beta_1$, $\beta_2$, and $\beta_3$, indicating how the supply shocks of inventors in collaboration space, geographic space, and idea space affect firm outcomes, respectively.

In the next subsection, I account for possible endogeneity issues when unobserved characteristics would affect the innovation rates of firms, thereby biasing the OLS coefficients.

## 4.2 Accounting for endogeneity

Firms that lost many inventors to WWI military service may differ in various characteristics from firms that lost few inventors. The innovation rates of these two kinds of firms are assumed to not differ in the absence of supply shocks. On the condition that men registered, more than 90 percent of the population who had served were drafted. Therefore, the majority of inventors who had registered and served were involuntarily drafted. However, inventors were not random subsamples of the total population of draft-eligible males, and thus, it was not evident that this percentage held for inventors. Furthermore, those who were drafted could evade the draft, fail their physical examinations, or claim exemption during their appearance before the local board.

The above characteristics of firms and drafts could have biased the OLS coefficients. The assumption that the majority of inventors who had registered and served were involuntarily drafted and inducted into the military could be weakened. For example, if inventors who had voluntarily served were more productive and motivated than other inventors, this could differentially impact the innovation rates within firms. To address these concerns, I propose the draftable age group to construct an instrument for each of the supply shocks.

The instruments rely on the age profile of the inventors. Only the third draft registration required registration by all men aged 18 to 45. Specifically, 95 percent of inductions came from the first and second registrations. The third registration took place on September 12, 1918, and numbers were drawn on September 30, 1918, just before WWI ended on 11 November, 1918. Because WWI ended two months after the third registration, the majority of inductions thus occurred in the first and second registrations, where young men were disproportionately likely to register. Furthermore, men aged 21 to 30 were less likely to fail their physical examinations when they were drafted and were less likely to file claims of dependents such as spouses or children. I find that inventors aged 21 to 30 were more than five times as likely to serve than inventors aged 31 or older (4 percent versus 0.7 percent). Thus, using variation in the proportion of inventors between the ages of 21 and 30 within given firms, geographic locations, and idea spaces, I am able to calculate powerful instruments for the proportion of such inventors who were drafted and served.

I first construct the instrument for the service rate in collaboration space. Let $P^*_{jCs}$ be the number of patent applications per year between 1910 and 1916 by inventors aged 21 to 30 at risk of being drafted, and let $P_{jC}$ be the pre-WWI patents by all inventors of firm $j$. I can then define the instrument for the supply shock in collaboration space as

$$S^*_{jC} = \frac{P^*_{jCs}}{P_{jC}} \tag{5}$$

The instrumental variable $S^*_{jC}$ measures the proportion of firm $j$'s team members who are at risk of being drafted and inducted during the WWI draft. The difference is that the age profile of the inventors is used instead of the military service record of the inventors.

Similarly, I construct the instrument for the supply shock in geographic space. Let $P^*_{Gs}$ be the number of pre-WWI patents annually by inventors between the ages of 21 and 30 who lived in county $G$, and let $P_G$ be the number of pre-WWI patents by all inventors in county $G$. The instrument for the supply shock in geographic space is then defined as

$$S^*_{jG} = \frac{P^*_{Gs}}{P_G} \tag{6}$$

The instrumental variable $S^*_{jG}$ measures the proportion of inventors who were at risk of being drafted and inducted in county $G$, where firm $j$ was located during the WWI draft.

Finally, I define the instrument for the supply shock in idea space using the field composition of firm $j$. Let $patent_{jf}$ be the number of pre-WWI patents in field $f$ by firm $j$ and $patent_j$ be the total number of pre-WWI patents by firm $j$. Then let $P^*_{fs}$ be the number of pre-WWI patents in field $f$ by inventors aged 21 to 30, and let $P_f$ be the number of pre-WWI patents in field $f$ by all inventors. The instrument is then constructed as

$$S^*_{jF} = \sum_f \frac{patent_{jf}}{patent_j} \frac{P^*_{fs}}{P_f} \tag{7}$$

The instrumental variable $S^*_{jF}$ measures the proportion of inventors at risk of being drafted in a similar field mix of firm $j$.

I use these variables constructed by draftable age group to develop the instrument to measure the supply shocks of inventors who served in the military. Figure 2 represents how many inventors served in the military within firms that contained many inventors of draftable age and within other firms that contained few inventors of draftable age in each of the spaces. I identify the two groups of firms using each of the instruments that measure supply shocks. Firms with many peers at risk of being served have values above the median, while firms with few peers have values equal to or below the median. This demonstrates that firms with many inventors of draftable age had higher service rates of inventors than other firms, thus leading to a large decline in the pool of inventors who could affect the innovation activities within firms.

In the next subsection, I explain how the dynamics of the effects are measured.

### 4.3 Effect relative to the year before the WWI draft

I complement my empirical analysis with a difference-in-differences specification relative to the base year prior to the WWI draft. This event study specification will provide evidence on the dynamics of the effect of supply shocks on a firm's innovation rate after controlling firm-specific characteristics and state-specific economic trends. I use the regression model

$$Y_{jt} = \sum_{t=1910}^{1918} \left[ \beta_{1t}(S^*_{jC} \times D_t) + \beta_{2t}(S^*_{jG} \times D_t) + \beta_{3t}(S^*_{jF} \times D_t) \right] + \theta X_{jt} + \gamma_j + \delta_{st} + \epsilon_{jt} \tag{8}$$

where $D_t$ is a year dummy, except the base year 1916, the year before the WWI draft. The instruments for supply shocks–$S^*_{jC}$, $S^*_{jG}$, and $S^*_{jF}$–that interacted with a set of indicator variables corresponding to a particular year, $D_t$, provide the reduced-form estimates relative to the base year. I also include state-by-year fixed effects, $\delta_{st}$. The parameters of interest, $\boldsymbol{\beta}_t$, therefore, measure the effect of the supply shocks on the innovation rates of firms in the year $t$ relative to the omitted base year 1916, before the WWI draft registrations and lotteries began in 1917.

# V Results

## 5.1 The effect of supply shocks on firms

The supply shocks of inventors as a result of the WWI draft affected the innovation rates of firms as measured by the number of patents. Figure A.3 illustrates the raw data on the number of patents by two types of firms. Figure A.3 clearly shows a decrease in the number of patents by firms that lost their team members. The supply shock in geographic space did not significantly impact a firm's innovation rate. Firms more exposed to the supply shock in idea space experienced an increase in innovation rates when they lost inventors outside the firms working on the same topics.

These results provide graphical evidence of the effects of supply shocks on firms' innovation rates but do not consider the presence of unobservable firm-specific factors and state-specific economic trends that could have impacted firm outcomes. Furthermore, two types of firms in Figure A.3 are defined by a median value of supply shocks that is actually a continuous variable. To address this issue, I show the dynamics of effects relative to the omitted year 1916, which is before the WWI draft. Specifically, Figure 3 shows the estimates of the regression model in equation (8) in each of the supply shocks, demonstrating that most of the estimated coefficients are insignificant before the omitted base year 1916. This result indicates that no differential pre-trends exist among firms. Consistent with the results of Figure A.3, the estimates shown in Figure 3 move in the same direction. The supply shock of team members decreased firms' innovation rates, but the supply shock of inventors in the space of ideas increased firms' innovation rates.

I use the regression model to investigate the effect of supply shocks on firm outcomes. In Table 2, I report the coefficients from the first-stage regressions.[10] The relationship between the instrument and the supply shock is presented in the first three columns. The last three columns show the coefficients when the three instruments are included at the same time in

[10] The first-stage regression equation is

$$\boldsymbol{S_j} \times T_t = \alpha_1(S^*_{jC} \times T_t) + \alpha_2(S^*_{jG} \times T_t) + \alpha_3(S^*_{jF} \times T_t) + \theta X_{jt} + \gamma_j + \delta_{st} + \epsilon_{jt}$$

where $\boldsymbol{S_j}$ is a vector of firm-specific supply shocks $(S_{jC}, S_{jG}, S_{jF})$ measured by inventors who served in the military and $S^*_{jC}, S^*_{jG}$, and $S^*_{jF}$ are firm-specific instruments measured by draftable inventors.

the regression. Each instrument for the supply shock in its space has a significantly positive effect on the proportion of inventors who served. The instrument for the supply shock in idea space is correlated with that in collaboration space, but the correlation coefficient is relatively small. The pairwise correlations among the three instruments range from 0.003 to 0.015. The multivariate F-test of excluded instruments produces high F statistics, indicating $p$ values close to zero. Firms with many inventors at risk experienced a decrease in the number of inventors in all three spaces from 1917 to 1918. This indicates that firms with a large portion of draftable inventors were more likely to lose inventors during the WWI draft. For example, the estimated coefficient in collaboration space suggests that a 10 percent supply shock of inventors of draftable age working with the firm, weighted by their pre-WWI patents, leads to a 1.1 percent supply shock of inventors who served, weighted by their pre-WWI productivity. In other words, an increase in the instrument in collaboration space by 0.1 increases the supply shock in collaboration space by 0.01065 (column 4).

Table 3 reports the estimated coefficients from IV specifications of the regression model,[11] and Table A.2 reports OLS estimates in equation (4). The analysis sample includes firms that had at least one patent application prior to the WWI draft and no patent applications within the arms industry, such as weapons, ammunition, and explosives. The dependent variable is the number of patent applications not belonging to the arms industry.

I find that the supply shock in collaboration space has a negative effect on the innovation rates of firms, while the supply shock in idea space has a positive effect on such rates. I also find a positive (though insignificant) effect of the supply shock in geographic space. In particular, a 10 percent decrease of inventors who worked with a firm weighted by their previous productivity–that is, an increase in the supply shock in collaboration space by 0.1–decreases the number of patent applications per year by 0.01946 (column 4, Table 3). Given the average number of patents per year by firms (0.1618), the loss of 10 percent of team members who served reduces patent applications by a 12 percent. The loss of 10 percent of inventors in idea space increases the number of patents annually by 0.01262 (column 4),

[11] The second-stage regression equation is

$$Y_{jt} = \beta_1(\widehat{S_{jC}} \times T_t) + \beta_2(\widehat{S_{jG}} \times T_t) + \beta_3(\widehat{S_{jF}} \times T_t) + \theta X_{jt} + \gamma_j + \delta_{st} + \epsilon_{jt}$$

associated with an 8 percent increase in the number of patents. This suggests that a firm experiences an increase in innovation rates given a loss of inventors outside the firm yet working in the same industry.

The overall effects are shown in the first panel of Table 3. I now consider that the relative strength of these effects can vary depending on how close the firms are to the knowledge frontier. For example, some firms close to the knowledge frontier could be more innovative and productive given the loss of inventors in idea space because of less competition within a field, but other firms could be less innovative because they depend heavily on knowledge spillovers. To investigate this, I create different groups of firms depending on their innovation activities before the shock.

I identify two groups of firms based on the average number of pre-WWI patent applications per year. The results for highly innovative firms with numbers of pre-WWI patents above the median are consistent with the main findings. Specifically, a 10 percent increase in the supply shock in collaboration space leads to a 10 percent decrease given the average number of patents. I also find that a 10 percent increase in the supply shock in idea space increases patent applications by 8 percent.

Less innovative firms are defined as firms that had pre-WWI patent applications per year equal to or below the median. A 10 percent supply shock in collaboration space results in a 3 percent (insignificant) decrease in patents. Interestingly, the supply shock in idea space has a significantly negative effect on the innovation rates of less innovative firms. In particular, a 10 percent supply shock in idea space decreases the number of patents per year by 0.00649 (column 4), associated with an 8 percent decrease in patent applications. Highly innovative firms benefit from the loss of inventors in the space of ideas, but less innovative firms suffer from the loss of inventors in the industry who generate knowledge spillovers. This provides evidence that firms close to the knowledge frontier create new ideas given less competition in idea space, but less innovative firms depends heavily on knowledge spillovers in the same space.

I report the regression results of the reduced form in Table 4. Specifically, I estimate the effect using the regression model in equation (4) in which the supply shocks $(S_{jC}, S_{jG}, S_{jF})$

are replaced with the instruments ($S^*_{jC}, S^*_{jG}, S^*_{jF}$), respectively.[12] The parameters of interest measure the effect of the loss of draftable inventors on patenting by firms. The results are consistent with the IV estimates. The supply shock of inventors working with the firm decreases the firm's innovation rates, but the supply shock of inventors outside the firm working on the same topics increases the firm's innovation rates. The latter effect is driven by more innovative firms, while less innovative firms experience a decline in invention in response to the loss of inventors in the space of ideas.

I estimate the long-run effect of supply shocks on the innovation rates of firms. I investigate whether the effect of the supply shocks of the loss of inventors is persistent using the reduced form. The empirical analysis above uses years between 1910 and 1918, thus defining the pre-treatment period as the years between 1910 and 1916 and the post-treatment period as the years between 1917 and 1918. To estimate the long-run effect, I examine several modifications of the pre- and post-treatment periods. In Table A.3, the reduced-form estimates are reported to rely on the different pre- and post-treatment years. I also report the subsamples of more and less innovative firms in Table B.2 and Table B.3, respectively. The supply shocks in geographic space and idea space have negative effects on the innovation rates of firms in the long term, which is inconsistent with the main findings between 1910 and 1918. Table B.2 and Table B.3 show that the results are driven by less innovative firms. However, a positive effect of the supply shock in idea space is still persistent for highly innovative firms, reported in Table B.4. The results in the long run are less precisely measured because of the possibility that firms might change their names or locations over time. To address this issue, I explore the industry level of analysis in the mechanism.

[12]The reduced-form regression equation is

$$Y_{jt} = \beta_1(S^*_{jC} \times T_t) + \beta_2(S^*_{jG} \times T_t) + \beta_3(S^*_{jF} \times T_t) + \theta X_{jt} + \gamma_j + \delta_{st} + \epsilon_{jt}$$

## 5.2 Robustness of results

### 5.2.1 Validity of the instrument

The validity of the IV estimates relies on the consistency of innovation rates in the absence of the WWI draft among firms with and without draftable inventors. Specifically, the outcome of firms more exposed to inventors of draftable age and the outcome of firms less exposed to inventors in draftable age do not change differently in the absence of the shock, and the shock to the labor supply of inventors of draftable age affects the firm outcome through the military service. To support this identifying assumption, I implement a placebo test using inventors in different age groups. Placebo supply shocks are created using inventors older than 30 years old. Inventors aged 30 or below were more likely to have been drafted or enlisted in the military from the first and second draft registrations. Inventors aged 31 to 45 registered in the third draft registration but rarely served. Furthermore, inventors aged 46 or above were not required to register and thus were not draftable. This would suggest that no relationship exists between placebo supply shocks of less draftable or undraftable inventors and firm's innovation rates since firms did not lose inventors older than 30 years old who rarely served.

I first investigate which age groups are more likely to serve in the military. I report correlations between placebo supply shocks and actual supply shocks in Table B.5. Panel A presents the correlation between supply shocks of draftable inventors and supply shocks of served inventors. The correlations among each supply shock of different age groups corresponding to the actual supply shock of inventors who served in each space are shown to be substantial. However, the placebo supply shocks within panels B and C are not significantly correlated with the actual supply shocks. Table B.6 shows first-stage regressions using placebo age groups. The estimated coefficients were quite small compared to the estimates reported in Table 2. Furthermore, the low F statistics confirm that placebo supply shocks do not have a strong first stage. This provides evidence that inventors older than 30 years old did not serve in the military and that firms did not lose those inventors in the three spaces in the regression analysis.

Table 5 reports reduced-form OLS coefficients using placebo supply shocks. The coefficients are small and insignificant in all specifications, indicating no evidence exists of any reduced-form relationship between placebo supply shocks and the innovation rates of firms. No relationship was also found between placebo supply shocks and firm's innovation rates using the IV estimates (Table B.7).

Another threat to the validity of the instruments involves the possibility that the shock before the WWI draft affects the innovation rates of firms differently. I provide evidence on common pre-trends among firms shown in Figure 3, but I can also examine placebo tests treating each of the years prior to the WWI draft of 1917-1918 as a placebo draft year. Figure B.5 and Table A.4 present the results of the placebo draft year. No evidence was found of significant impacts of supply shocks on inventions in each prior year, demonstrating that the pre-trends captured by the WWI shock prior to the WWI draft do not alter the results of this study.

#### 5.2.2 Controlling for the government's effect

Any labor shock that occurred during WWI but was not captured by the WWI draft and military service might have also differentially impacted firms. For this reason, I only consider patents that are unrelated to the arms industry. In addition, firms that worked closely with the government might have been differently affected by such supply shocks. The firms would increase inventions if the government supported or invested in them when the United States entered the war and invested heavily in war-related efforts. Furthermore, inventors working with firms that were close to the government or the arms industry might have been unlikely to be drafted, even if those inventors were 21 to 30 years old, which leads to biased results.

To address these concerns, I identify which firms and patents are related to the government. I then use the sample of firms that had no patent applications with the government prior to the WWI draft, and I also use the outcome of patents not assigned to the government. I find that the results are similar to the main findings in every respect (Table A.5). This provides evidence that the measured effects of supply shocks on firms' innovation rates are valid after controlling for the government's effect.

### 5.2.3 Alternative specifications

I consider a number of alternative specifications to show that the results are robust to several modifications to the main estimation equation. I first use all firms and all patents regardless of their relationship to the arms industry. I find that the results reported in Table B.8 using the reduced form are robust.

I directly measure the differential effects of supply shocks on the innovation rates of firms depending on their pre-WWI innovation rates. I include an interaction term for two groups of firms (more innovative firms and less innovative firms) rather than restrict the full sample to two subsamples. Table B.9 reports the reduced-form estimates with the interaction term. Consistent with the results using the subsamples, more innovative firms experienced an increase in innovation rates when they lost inventors in idea space, while less innovative firms experienced in a decrease in innovation rates in response to such a supply shock.

The number of patents includes a large proportion of zeros in the panel data. I thus consider the Poisson regression of the reduced form to address the nature of the data. I find that the results are similar, but a fixed effect for firms is not included.[13]

I also consider a slightly modified form of supply shocks. I modify the supply shock in collaboration space. In the previous specification, I only consider the productivity of the inventors. In the modified supply shock, I consider how close the firm and the inventors are as well as inventor productivity. I use the number of patents between 1910 and 1916 by firm $j$ together with inventors who worked with firm $j$ when $P_{jCs}$ and $P_{jC}$ are defined. Therefore, considering the supply shock for firm $j$ depends on how closely the inventors worked with firm $j$ before the shock. The results are very similar (Table B.10).

In another modified form of supply shocks, I replace supply shocks in geographic space and idea space with those measured by inventors who were not team members. For example, suppose an inventor in county $c$ worked with firm $j$ in field $f$. This inventor is used to calculate the supply shocks in the three spaces, i.e., supply shock in collaboration space for

[13] Standard regression packages such as *poisson* and *xtpoisson* lead to convergence problems for the maximum likelihood because of a fixed effect for firms that had few patents (Santos Silva and Tenreyro, 2010, 2011; Waldinger, 2012). Although I use the *ppml* command to address this problem, as suggested by Santos Silva and Tenreyro (2011), the regression does not produce the results because of a large number of observations with a fixed effect.

firm $j$, supply shock in geographic space for firm $j$, located in county $c$, and supply shock in idea space for firm $j$ in field $f$. In the modified form of supply shocks, an inventor used to measure the supply shock in collaboration space is not used to measure the supply shocks in geographic space and idea space. Specifically, the supply shock in geographic space for firm $j$ in county $c$ is measured by inventors in county $c$, excluding team members for firm $j$, and in the same fashion, the supply shock in idea space for firm $j$ in field $f$ is measured by inventors in field $f$, excluding team members for firm $j$. Although the regression analysis that includes the three shocks simultaneously provides the marginal effect of the supply shock while holding other supply shocks fixed, this modified form of supply shocks explicitly excludes inventors inside the firm when the supply shocks in geographic space and idea space indirectly affect firm outcome. I report the results in Table B.11 using the reduced form and find the results to be consistent with other models.

Additionally, I consider a supply shock of all men of draftable age in the 1910 census. I measure the effect of the supply shock of all men within geographic space on the innovation rates of firms while the other two supply shocks in collaboration space and in idea space remain the same. I find no evidence of relationships among the supply shocks of all men and firm's inventions, as reported in Table B.12, Table B.13, and Table B.14. This suggests that the overall loss of workforce in the county does not affect the innovation rates of firms located in the same county. However, which firms they work for is not identified.

Finally, I only consider inventors not working with any firm once measuring the effects of the loss of inventors working in the same geographical location and losing inventors working in the same industry. This analysis allows me to explicitly compare the negative competition effects with knowledge spillovers in geographic space and in idea space because inventors work alone as freelancers or in a team with other individuals but they are not connected with any firm in geographic space and in idea space. I report the results in Table B.15 using the reduced form and find the results to be consistent. To compare the magnitude of the effects using this specification with main results in Table 3, I also report the results in Table B.16 using the IV method. Specifically, the loss of 10 percent of the inventors not working with any firm but working in the same industry increases the firm's innovation rate by 5 percent. This effect is clearly driven by negative competition effects in the industry because the loss of inventors does not directly affect firms. This suggests that firms can be more innovative when potential competitors in the field disappear and that negative competition effects dominate knowledge spillovers in the space of idea.

# VI Mechanism

## 6.1 The effect on individuals

Inventors as well as firms play a crucial role in creating new ideas and inventions. Because inventors may depend heavily on knowledge spillovers or may find it difficult to obtain patents for the first time, I consider the effects of supply shocks on patenting by inventors. The aggregated data on patents by inventors does not represent patents by firms, and inventors could work as individuals or in a team or work for a single firm or several firms. Thus, this analysis seeks to understand the channels through which inventors generate knowledge spillovers and which individuals depend heavily on spillovers in response to the loss of their peers. I focus on inventors who did not serve in the military when they had lost peers because of the WWI draft. The impact of peers on the level of innovation of inventors who did not serve in the military could be a key driver of patenting by firms in response to the supply shocks of losing peers. The online Appendix contains details of this analysis.

The results demonstrate that the innovation rates of inventors who did not serve were negatively impacted when they had lost peers in their collaboration spaces. Inventors and entire firms experience a large decline in their inventions when they lose their team members. I find that inventors benefit from the supply shock in idea space less than firms. Firms substantially experience an increase in their innovation rates when they lose potential competitors in idea space, but inventors gain less benefits from losing peers in the same space. I also find that the supply shock in idea space has a strong positive effect on the innovation rates of both young and more productive inventors before the shock and more innovative firms, which had more innovation activities before the shock. These results prove that the position of knowledge producers relative to the frontier in their field plays a role in explaining peer effects when they lose peers.

## 6.2 The effect on new entrants and the industry

The long-run impact on innovations and growth should be well understood, but using the firm panel data measuring in the long-run impact is problematic because the firm could change its name or location over time. The industry-level analysis addresses this issue and allows me to explore the mechanism by which the loss of inventors in the industry attracts a new group of inventors and firms to the industry. To investigate this mechanism, I measure the year of entry into an industry using an inventor's or firm's first patent to a patent industry class.

I employ difference-in-differences specifications to investigate the impact of the supply shocks at the industry level. The regressions estimate

$$Y_{it} = \beta(S_i^* \times T_t) + \gamma_i + \delta_t + \epsilon_{it} \tag{9}$$

where $Y_{it}$ is the number of new inventors, firms, or patent applications for industry $i$ in year $t$. The variable of $S_i^*$ represents the loss of inventors in the industry measured by the proportion of inventors of draftable age in industry $i$. I include industry fixed effects ($\gamma_i$) and year fixed effects ($\delta_t$).

The estimates indicate that 47.1 new inventors and 5.5 new firms per industry and year entered the industry when the industry had lost 10 percent of inventors (Panel A of Table A.6). In particular, a 10 percent decrease in inventors working in the industry attracts 25 percent additional inventors and 21 percent additional firms given the average of entrants to the industry. Because of these new entrants, the industry's overall innovation activity is not significantly affected. I also find that these effects persist in the long run. This implies that the loss of inventors in the industry helps attract new entrants to the industry, suggesting that an increase in inventions by new inventors and firms offsets a decrease in inventions from the loss of inventors.

Another caveat to the firm-level analysis is that other firm-level outcomes are unavailable. Given this caveat, I conduct an industry-level analysis using information from the 1920 Census of Manufactures. I find that the loss of inventors and workers in the industry reduces wages per capital and workers per establishment (Table B.22). Hence, labor intensity and firm size decrease in an industry that experiences a decrease in high-skilled workers and its total workforce. However, they are statistically insignificant and less precisely estimated because only 14 industry classes over the years are available.

### 6.3 Highly innovative firm

I investigate how the effect of the supply shocks varies with the productivity of firms. The main results are driven by more innovative firms, but firms could be categorized more specifically other than pre-WWI patents above the median. To understand clearly how the results are driven, I use different subsamples of highly innovative firms. This analysis contributes to a growing literature that examines how the careers of knowledge producers, the quality of their outputs, and the quality of their peers affect their productivity and outcomes (Azoulay et al., 2010; Waldinger, 2010, 2012; Iaria et al., 2018; Bell et al., 2019a). Specifically, I determine whether the supply shocks have a large impact on highly innovative firms rather than on other firms.

I reestimate innovation rates within the subsamples. Table A.7 reports the reduced-form estimates using the subsamples of top innovative firms. I find that firms in the top fifth percentile of inventions experience a decrease in their patent applications per year by 0.5824, translating into a 3 percent decrease when those firms face a 10 percent supply shock of team members. Instead, those firms experience a substantial increase in their innovation rates when they lose their competitors in idea space. Specifically, patent applications increase by 7.8 percent in response to a 10 percent supply shock in idea space. The results for firms in the top tenth and twenty-fifth percentiles are similar to those for firms in the top fifth percentile. The reduced-form estimates using the full sample in the same specification reported in Table 4 show that losing 10 percent of inventors in collaboration space and idea space affect the inventions of firms through a 1.3 percent decrease and a 3.9 percent increase, respectively. These findings indicate that highly innovative firms are most affected by the supply shocks.

I additionally measure the differential effects of supply shocks on the innovation rates of firms depending on their pre-WWI patents. I include an interaction term for presenting the percentile in their pre-WWI patents. Table B.23 reports reduced-form estimates with the interaction term. The first three rows show the results for firms at the bottom percentile in pre-WWI patents without any interaction term, and the next three rows show the differential effects of the supply shocks when firms increase their pre-WWI patents by one percentile. The results here suggest that the closer the firms get to the knowledge frontier, the more their patent applications increase in response to the loss of inventors in the space of ideas.

## 6.4 New ideas

To see which firms create new ideas in response to which shocks, I determine whether the supply shocks affect new ideas introduced by firms using an alternative dependent variable: original patent application. Through textual analysis, I construct an indicator from the new words identified from patent titles by first defining any words contained in patent titles in 1900 as new words. Then words that already appeared in previous patent titles are defined as non-novel. I then defined a dependent variable of the number of original patent applications containing at least one new word that had not already appeared in previous patent titles.

Table A.8 reports the reduced-form estimates using original patent applications as a dependent variable. No significant effects of supply shocks on the number of original patents are reported. However, highly innovative firms create more original ideas when they lose inventors in the space of ideas (Table B.24). This supports the hypothesis that highly innovative firms at the knowledge frontier create new ideas.

## 6.5 Citations

Firms are assumed to have invested most heavily in the most successful inventions rather than marginal inventions. To investigate whether the supply shocks affect patents weighted by the later influence of the invention, I re-estimate the results in Table 4, with patent citations as the outcome variable. The results are similar to the supply shocks shown in Table A.9, but the impact of the supply shock in idea space varies more heavily with firms' previous innovation rates. More innovative firms experience a large increase in citation-weighted patents in the space of ideas, while less innovative firms experience a significant decrease. Moreover, I find evidence that highly innovative firms contribute to more successful inventions in the space of ideas (Table B.25). Thus, these results indicate that highly innovative firms act as knowledge frontiers by investing more in useful inventions, while less innovative firms depend more on knowledge spillovers.

## 6.6 Quality of inventors

Firms aim to attract highly skilled workers and productive inventors to encourage innovation and increase productivity. Inventor quality is considered one of the key drivers for firm innovation. However, whether this positive relationship between inventor quality and firm innovation leads to a causal relationship is undetermined. To identify the causal effect of inventor quality on a firm's innovation rate, I measure the effect of the supply shocks depending on the distribution of inventor quality on the innovation rates of firms.

Table 6 reports the reduced-form estimates relying on the supply shocks of different quality inventors in place of all inventors shown in Table 4. The results are similar if firms lose high-quality inventors who worked for them or collaborated with them. The supply shock of losing high-quality or low-quality inventors in the space of ideas increases the firms' innovation rates. Interestingly, I find that the supply shock of losing high-quality inventors in geographic space decreases the innovation rates of firms, but the supply shock of low-quality inventors increases the innovation rates. Thus, the overall effect of the loss of inventors in geographic space is cancelled out (Table 4). This provides empirical support for previous findings from existing studies of the dynamics of knowledge spillovers in geographic space. High-quality knowledge producers had large spillovers on geographically close others, but low-quality knowledge producers had a less than proportionate impact. The loss of low-quality inventors actually increases a firm's innovation.

I also investigate whether supply shocks have differential effects on a firm's invention depending on a firm's previous innovation rate, as shown in Table B.26 and Table B.27 for more innovative firms and less innovative firms, respectively. More innovative firms benefit more from losing more productive inventors in similar topics, but less innovative firms experience a larger decline in invention when they lose more innovative inventors. This supports the hypothesis that highly innovative firms act as knowledge frontiers that fill a gap immediately, but less innovative firms depend on knowledge spillovers.

In sum, I find evidence of the causal relationship between inventor quality and a firm's innovation rate. The loss of high-quality inventors has larger effects on the innovation rates of firms than losing other inventors. Highly innovative knowledge producers have large spillovers, thus largely affecting firm innovation. The results here provide evidence on the importance of the quality of knowledge producers that are consistent with those of previous studies (Waldinger, 2010; Iaria, Schwarz, and Waldinger, 2018). Inventor quality is an important determinant of firm innovation, and high-quality inventors are not replaceable in the invention production of the firm.

# VII Conclusion

In this paper, I provide the first causal evidence of the supply shocks of inventors on a firm's innovation activity. I use a novel approach to answer this question by creating new matched data and exploiting the new natural experiment of the WWI draft and subsequent military service of inventors in which firms exogenously lose inventors. I distinguish the separate effects of the loss of inventors on a firm's innovation rate. A firm could lose inventor team members who worked directly for or with the firm because of WWI military service. The firm could also lose inventors close to its location in geographic space (working in the same county) and idea space (working in the same industry).

My analysis revealed four major findings. First, the loss of inventors who work for a firm decreases the firm's innovation rate. Consistent with the results of previous empirical studies and the theory of human capital externalities, the loss of team members has a significant negative impact on the productivity of knowledge producers.

Second, I find that the loss of inventors working in the same county does not significantly affect the firm's innovation rate. The quality of inventors provides evidence on how the overall effect of the loss of inventors from the same county is cancelled out. The negative competition effects are enough to offset knowledge spillovers generated by high-quality inventors in geographic space.

Third, I find that the loss of inventors working in the same industry in which a firm engages increases the firm's innovation rate. This increase suggests that the negative competition effects and the law of diminishing returns prevail over knowledge spillovers in the space of ideas. Intense competition exists in the space of ideas, and inventors who are not team members of a firm in the same industry have a negative impact on the firm's innovation rate. This result provides evidence that new ideas grow when other knowledge producers in the field leave, consistent with Planck's principle that a "new generation grows up when its opponents die."

Fourth, the effects of supply shocks on a firm's innovation rate depend on how close the firm is to the knowledge frontier and inventor quality. The overall results are driven by frontier firms and high-quality inventors. Firms that are highly innovative prior to the WWI draft benefit from the loss of inventors outside those in the same industry, but less innovative firms experience a decrease in innovation rates in response to such a supply shock in idea space. This result proves that less innovative firms depend heavily on knowledge spillovers. As inventors in the industry are removed to serve in the military during WWI, producers in the knowledge frontier fill the empty space of ideas.

Taken together, these results provide a deeper understanding of the dynamics of knowledge spillovers and how innovation rates depend on the distribution of inventors across firms and the space of ideas. However, all the evidence presented here pertains to firms' inventions during the early twentieth century, a time during which the system of mass production was introduced in the United States. How these findings might extend to current industries or other areas of knowledge production is unclear. In particular, an increase in the mobility of skilled labor may generate large spillovers in the geographic space as they move from one location to another more frequently, but at the same time, a rise in working remotely or from home is unlikely to generate peer effects. Furthermore, the importance of capital equipment and collaborative work in inventive activity differs across the industry. For example, industrial research in some fields could not be conducted without capital equipment and collaborative work and thus is likely to evolve by incumbent frontier firms that already possess specialized equipment and rich collaborative networks. In contrast, other fields in which researchers tend to work alone and in which capital equipment is less required may provide more opportunities for newcomers to produce new inventions. Therefore, future research should address where these new inventions tend to originate.

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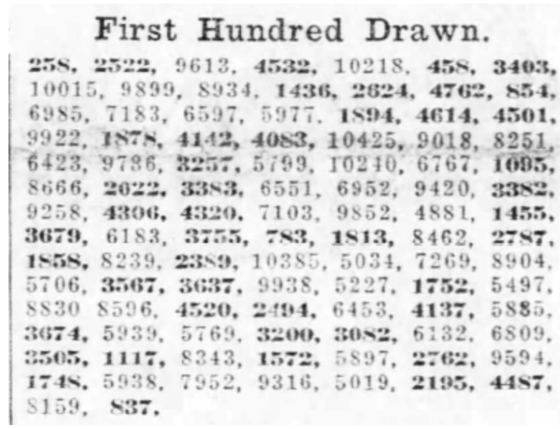
Figure 1: WORLD WAR I DRAFT LOTTERY

(a) The first draft number in the lottery



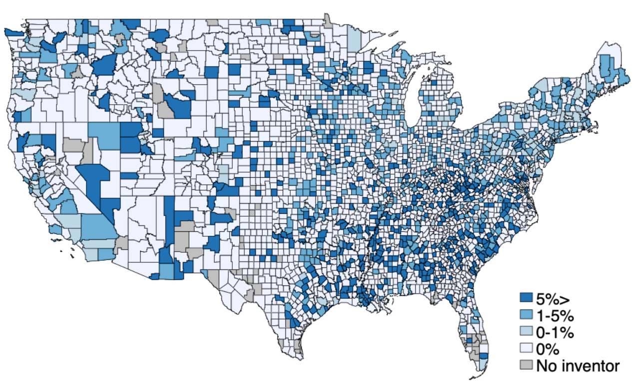
**First Hundred Drawn.**

258, 2522, 9613, 4532, 10218, 458, 3403, 10015, 9899, 8934, 1436, 2624, 4762, 854, 6985, 7183, 6597, 5977, 1894, 4614, 4501, 9922, 1878, 4142, 4083, 10425, 9018, 8251, 6423, 9786, 3257, 5799, 10240, 6767, 1095, 8666, 2022, 3383, 6551, 6952, 9420, 3382, 9258, 4306, 4320, 7103, 9852, 4881, 1455, 3679, 6183, 3755, 783, 1813, 8462, 2787, 1858, 8239, 2389, 10385, 5034, 7269, 8904, 5706, 3567, 3637, 9938, 5227, 1752, 5497, 8830 8596, 4520, 2494, 6453, 4137, 5885, 3674, 5939, 5769, 3200, 3082, 6132, 6809, 3505, 1117, 8343, 1572, 5897, 2762, 9594, 1748, 5938, 7952, 9316, 5019, 2195, 4487, 8159, 837.

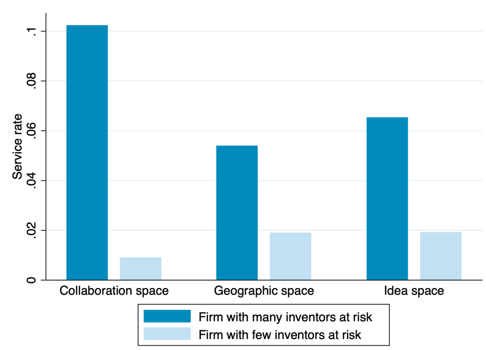
(b) The order of the first hundred numbers drawn

*Notes:* Secretary of War Newton D. Baker drew the first draft number in the lottery shown in the first figure. The order of the first hundred numbers drawn from the first registration was published to the public (Pittsburgh Post on July 21, 1917).

Figure 2: SUPPLY SHOCK OF INVENTORS




(a) Service rates in county



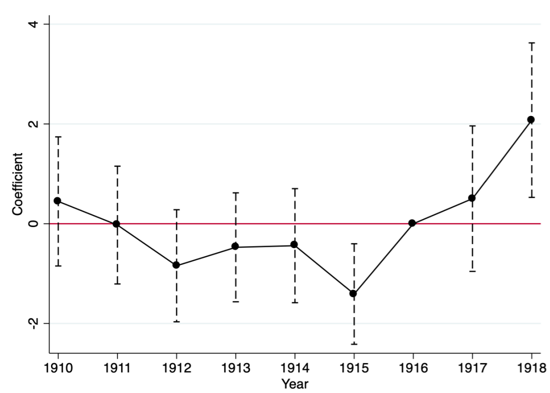

(b) Service rates for firms

*Notes:* The figures show a supply shock of inventors because of the WWI draft and military service. The first figure presents inventors who served in the military as a percentage of total inventors in each U.S. county. The second figure shows the percentage of inventors who served in the military for firms with many inventors at risk which had a portion of inventors of draftable age above the median and firms with few inventors at risk which had a portion of inventors of draftable age equal to or below the median in each space, respectively.

Figure 3: IMPACT OF SUPPLY SHOCK ON INNOVATION RATES RELATIVE TO A YEAR BEFORE THE WWI DRAFT


(a) Collaboration space


(b) Geographic space




(c) Idea space

*Notes:* The figures show the estimated coefficients relative the base year 1916 from the event study specification in each space, respectively. The sample consists of firms which had at least one patent application prior to the WWI draft and no patent application belonging to the arms industry, such as weapon, ammunition, and explosives. The outcome variable is the number of patent applications per year not relevant for the arms industry. The number of patent applications is winsorized at 10.

Table 1: SUMMARY STATISTICS

| | Mean (1) | Median (2) | SD (3) | Min. (4) | Max. (5) |
|---|---|---|---|---|---|
| *Patent applications per year* | | | | | |
| 1910-1918 | 0.1389 | 0 | 0.5237 | 0 | 10 |
| 1910-1916 (before the draft) | 0.1618 | 0 | 0.5602 | 0 | 10 |
| 1917-1918 (during the draft) | 0.0589 | 0 | 0.3567 | 0 | 10 |
| *Number of inventors* | | | | | |
| In collabroation space | 3 | 2 | 2 | 1 | 81 |
| In geographic space | 554 | 347 | 625 | 0 | 2,145 |
| In idea space | 1,063 | 36 | 3,143 | 0 | 36,758 |
| *Number of firms* | | | | | |
| | 29,031 | | | | |

*Notes:* The sample consists of firms which had at least one patent application prior to the WWI draft and had no patent application relevant for the arms industry, such as weapons, ammunition, and explosives. Patent applications per year is not relevant for the arms industry, winsorized at 10. The number of inventors represents the number of inventors per firm in each of three spaces between the years 1910 and 1918.

Table 2: FIRST-STAGE REGRESSIONS

| | Dependent variable | | | | | |
|---|---|---|---|---|---|---|
| *Instrument* | Collaboration (1) | Geographic (2) | Idea (3) | Collaboration (4) | Geographic (5) | Idea (6) |
| *Collaboration* ($S^*_{iC}$) | 0.1064*** | – | – | 0.1065*** | 0.0002* | -0.0000 |
| | (0.0051) | | | (0.0051) | (0.0001) | (0.0004) |
| *Geographic* ($S^*_{iG}$) | – | 0.5693*** | – | -0.0010 | 0.5692*** | 0.0163 |
| | | (0.0120) | | (0.0025) | (0.0120) | (0.0172) |
| *Idea* ($S^*_{iF}$) | – | – | 0.6690*** | 0.0238*** | 0.0004 | 0.6690*** |
| | | | (0.0092) | (0.0090) | (0.0003) | (0.0092) |
| F-test of excluded instruments | 438.10 | 2,236.66 | 5,261.10 | 147.10 | 795.51 | 1,810.59 |
| Number of observations | 261,279 | | | | | |
| Number of firms | 29,031 | | | | | |

*Notes:* The sample consists of firms which had at least one patent application prior to the WWI draft and had no patent application relevant for the arms industry, such as weapons, ammunition, and explosives. Standard errors are clustered by firms.

Table 3: IMPACT OF SUPPLY SHOCK ON INNOVATION RATES, IV COEFFICIENTS

| | Specification | | | |
|---|---|---|---|---|
| | (1) | (2) | (3) | (4) |
| *Dependent variable: Patent applications per year* | | | | |
| *A. Firms* | | | | |
| Supply shock in Collaboration space $\beta_1$ | -0.2000*** (0.0685) | – | – | -0.1946*** (0.0683) |
| Geographic space $\beta_2$ | – | 0.0630 (0.0781) | – | 0.0639 (0.0777) |
| Idea space $\beta_3$ | – | – | 0.1201** (0.0549) | 0.1262** (0.0549) |
| Dependent variable mean | 0.1618 | | | |
| Number of observations | 261,279 | | | |
| Number of firms | 29,031 | | | |
| *B. More innovative firms* | | | | |
| Supply shock in Collaboration space $\beta_1$ | -0.3596* (0.2008) | – | – | -0.3334* (0.1997) |
| Geographic space $\beta_2$ | – | 0.4072 (0.2676) | – | 0.4136 (0.2673) |
| Idea space $\beta_3$ | – | – | 0.2646** (0.1233) | 0.2729** (0.1232) |
| Dependent variable mean | 0.3481 | | | |
| Number of observations | 81,837 | | | |
| Number of firms | 9,093 | | | |
| *C. Less innovative firms* | | | | |
| Supply shock in Collaboration space $\beta_1$ | -0.0175 (0.0260) | – | – | -0.0192 (0.0259) |
| Geographic space $\beta_2$ | – | -0.0435 (0.0344) | – | -0.0434 (0.0343) |
| Idea space $\beta_3$ | – | – | -0.0657*** (0.0207) | -0.0649*** (0.0207) |
| Dependent variable mean | 0.0768 | | | |
| Number of observations | 179,442 | | | |
| Number of firms | 19,938 | | | |

*Notes:* The sample consists of firms which had at least one patent application prior to the WWI draft and had no patent application relevant for the arms industry, such as weapons, ammunition, and explosives. More innovative firms had pre-WWI patents above the median and less innovative firms had pre-WWI patents equal to or below the median. The outcome variable is the number of patent applications per year not relevant for the arms industry. The number of patent applications is winsorized at 10. Standard errors are clustered by firms. State-year fixed effects are included.

Table 4: IMPACT OF SUPPLY SHOCK ON INNOVATION RATES, REDUCED FORM

| | Specification | | | |
|---|---|---|---|---|
| | (1) | (2) | (3) | (4) |
| *Dependent variable: Patent applications per year* | | | | |
| *A. Firms* | | | | |
| Supply shock in Collaboration space | -0.0213*** (0.0077) | – | – | -0.0208*** (0.0077) |
| Geographic space | – | 0.0366 (0.0481) | – | 0.0367 (0.0481) |
| Idea space | – | – | 0.0806** (0.0390) | 0.0793** (0.0390) |
| Dependent variable mean | 0.1618 | | | |
| Number of observations | 261,279 | | | |
| Number of firms | 29,031 | | | |
| *B. More innovative firms* | | | | |
| Supply shock in Collaboration space | -0.0370* (0.0217) | – | – | -0.0340 (0.0217) |
| Geographic space | – | 0.2322 (0.1627) | – | 0.2303 (0.1624) |
| Idea space | – | – | 0.1827** (0.0901) | 0.1795** (0.0901) |
| Dependent variable mean | 0.3481 | | | |
| Number of observations | 81,837 | | | |
| Number of firms | 9,093 | | | |
| *C. Less innovative firms* | | | | |
| Supply shock in Collaboration space | -0.0019 (0.0030) | – | – | -0.0021 (0.0030) |
| Geographic space | – | -0.0254 (0.0212) | – | -0.0252 (0.0212) |
| Idea space | – | – | -0.0432*** (0.0144) | -0.0433*** (0.0144) |
| Dependent variable mean | 0.0768 | | | |
| Number of observations | 179,442 | | | |
| Number of firms | 19,938 | | | |

*Notes:* The sample consists of firms which had at least one patent application prior to the WWI draft and had no patent application relevant for the arms industry, such as weapons, ammunition, and explosives. More innovative firms had pre-WWI patents above the median and less innovative firms had pre-WWI patents equal to or below the median. The outcome variable is the number of patent applications per year not relevant for the arms industry. The number of patent applications is winsorized at 10. Standard errors are clustered by firms. State-year fixed effects are included.

Table 5: IMPACT OF PLACEBO SUPPLY SHOCK ON INNOVATION RATES, REDUCED FORM

| | Specification | | | |
|---|---|---|---|---|
| | (1) | (2) | (3) | (4) |
| *Dependent variable: Patent applications per year* | | | | |
| *A. Supply shock of less likely draftable inventors (age 31-45)* | | | | |
| Supply shock in Collaboration space | -0.0024 (0.0048) | – | – | -0.0020 (0.0050) |
| Geographic space | – | -0.0123 (0.0165) | – | -0.0108 (0.0170) |
| Idea space | – | – | -0.0165 (0.0247) | -0.0166 (0.0247) |
| *B. Supply shock of not draftable inventors (age 46 or above)* | | | | |
| Supply shock in Collaboration space | 0.0040 (0.0045) | – | – | 0.0031 (0.0045) |
| Geographic space | – | 0.0176 (0.0172) | – | 0.0151 (0.0175) |
| Idea space | – | – | -0.0181 (0.0267) | -0.0178 (0.0267) |
| Dependent variable mean | 0.1618 | | | |
| Number of observations | 261,279 | | | |
| Number of firms | 29,031 | | | |

*Notes:* The sample consists of firms which had at least one patent application prior to the WWI draft and had no patent application relevant for the arms industry, such as weapons, ammunition, and explosives. The outcome variable is the number of patent applications per year not relevant for the arms industry. The number of patent applications is winsorized at 10. Standard errors are clustered by firms. State-year fixed effects are included.

Table 6: QUALITY OF INVENTORS AND IMPACT OF SUPPLY SHOCK ON INNOVATION RATES, REDUCED FORM

| | Specification | | | |
|---|---|---|---|---|
| | (1) | (2) | (3) | (4) |
| *Dependent variable: Patent applications per year* | | | | |
| *A. Supply shock of very high-quality inventors* | | | | |
| Supply shock in Collaboration space | -0.0512*** (0.0148) | – | – | -0.0480*** (0.0148) |
| Geographic space | – | -0.0643*** (0.0159) | – | -0.0601*** (0.0159) |
| Idea space | – | – | 0.0768* (0.0407) | 0.0770* (0.0408) |
| *B. Supply shock of high-quality inventors* | | | | |
| Supply shock in Collaboration space | -0.0511*** (0.0113) | – | – | -0.0481*** (0.0113) |
| Geographic space | – | -0.0633*** (0.0148) | – | -0.0577*** (0.0147) |
| Idea space | – | – | 0.0686* (0.0359) | 0.0679* (0.0360) |
| *C. Supply shock of low-quality inventors* | | | | |
| Supply shock in Collaboration space | 0.0015 (0.0121) | – | – | -0.0012 (0.0122) |
| Geographic space | – | 0.0501** (0.0195) | – | 0.0522*** (0.0198) |
| Idea space | – | – | 0.0452* (0.0236) | 0.0456* (0.0236) |
| Dependent variable mean | 0.1618 | | | |
| Number of observations | 261,279 | | | |
| Number of firms | 29,031 | | | |

*Notes:* The sample consists of firms which had at least one patent application prior to the WWI draft and had no patent application relevant for the arms industry, such as weapons, ammunition, and explosives. Very high-quality inventors had pre-WWI patents in the top 10 percentile. High-quality inventors had pre-WWI patents above the median and low-quality inventors had pre-WWI patents equal to or below the median. The outcome variable is the number of patent applications per year not relevant for the arms industry. The number of patent applications is winsorized at 10. Standard errors are clustered by firms. State-year fixed effects are included.