# 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. I construct a unique data set that contains matched firm-inventor patent data, WWI military records, and characteristics of inventors in the census, allowing me to use the World War I draft as an exogenous shock to the labor supply of inventors. I find that the loss of inventors working with the firm decreases the firm's inventions, but the loss of inventors in the same geographical location does not affect the firm's inventions. The loss of inventors outside the firm working in the same industry in the space of ideas increases the firm's inventions. This latter impact, however, varies considerably across firms: highly innovative firms experience an increase in innovation rates, while other firms decrease their innovation rates. Industry-level data indicate that the loss of inventors attracts new inventors and new firms to the industry. New ideas sprout when there exists a vacancy in the space of ideas.

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# I Introduction

The interest in knowledge spillovers goes back to at least Bernard in the 12th 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 it is clear that 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 natural experiments documented in the literature are conducted and read by individual knowledge producers, such as individual inventors and academic scientists. Firms account for 82 to 85 percent of U.S. patents between 2006 to 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.

Even though an inventor's human capital is presumably the most important input to a firm's knowledge production function, there are few studies of 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 inventor-firm data and use the World War I 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 due to the draft and military service.

The potential effects of the loss of inventors on firm innovation are not a priori obvious because inventors do not necessarily work for a single firm. For example, they can work alone as an entrepreneur, in a team with other individuals, or with several firms. Losing inventors who work directly with a firm or losing inventors 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. It is possible that inventors have negative competition effects on a firm's innovation activity. Losing inventors who compete with a firm as an entrepreneur or work with rivals of the firm could increase the chance that the firm increases its invention.

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; or (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 make use of a documented large labor supply shock that affected some inventors but not others: the United States draft during World War I. Due to the specificity of the age groups affected by the draft, some pools of inventors were heavily depleted during the war while other pools of inventors were left relatively unaffected. These differential effects occurred across all three types of inventors: team members at a firm, inventors working in the same county, and inventors working in the same industry. As a result, the data set I use in this study could be used to differentiate among the separate effects of losing 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 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 1920 Census. Using variation in the proportion of inventors in draftable age group, I use a difference-in-differences setup to identify the impact of losing inventors on a firm's invention. Specifically, I estimate 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 due to 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 in undraftable age groups 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. Losing inventors working with the firm as a team member decreases the firm's inventions, but losing inventors in the same geographical county does not significantly affect the firm's inventions. I find that losing inventors outside the firm 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 decrease 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 between firms. Within a firm, knowledge spillovers are powerful enough to negate any diminishing marginal returns to the firm's pool of inventors. Between firms, knowledge spillovers primarily work through 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 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 to attract new inventors and new 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 authors 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

[1] For example, Waldinger (2010) finds that PhD students suffer after superstar scientists who trained them emigrated. 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 U.S. 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).

each other's knowledge production.

Another perspective follows the law of diminishing marginal returns and negative competitive effects in which losing peers has a positive impact on the rate of knowledge production. This hypothesis suggests that knowledge producers take advantage of the decrease in competition within their field,[3] and thus have a negative impact on each other'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 losing inventors in a firm's team, within a geographic location, and within a particular idea space. 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 of previous studies 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 the theoretical model that explains how labor affects technology 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

[3] For example, Waldinger (2012) finds that researchers who were left behind after their colleagues emigrated did not decrease their productivity. Similarly, Borjas and Doran (2012, 2015b) examine the output of American mathematicians when Soviet mathematicians immigrated into the U.S. These authors find that American mathematicians in fields that received the influx of Soviet mathematicians experienced a decrease in the 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).

provide data and Section IV to present empirical strategies. I report the results in Section V and investigate the channels though which supply shocks affect firm-level innovation in Section VI. I provide a conclusion to the study in Section VII.

# II Historical Context

World War I began in Europe on July 28, 1914, with the U.S. 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 U.S., 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 for the years of 1917 and 1918. Figure A.1 shows how many persons were engaged in military service over time (Kendrick, 1961). The labor force in the public sector thus significantly increased at the time of the WWI draft (Figure B.1).[7] Military expenditures in Figure B.2 also surged when the U.S. entered the war, with one fifth of U.S. resources spent on the war effort (Rockoff, 2004).

Not all men who registered for the draft during WWI served in the military. Further, not all men who 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, served, and 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 11 November, 1918, the majority of men who were drafted and served through draft lotteries came from the first and second registrations. Fewer than

[7] Online Appendix Figure B and Table B are available from https://sites.google.com/site/chungeunyoon

200,000 men were inducted from the third registration despite about 13 million men having registered in the third round. Registrants provide their name, age, address, birth date, citizenship status and occupation on their draft registration card (Figure A.2).

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 registrants who were drafted eventually served in the military unless they claimed for exemption and their claim was granted. Fewer than 350,000 men who were selected were successful in gaining exemption.

The first national draft lottery held on July 20, 2017. The 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. There existed 4,648 local draft boards that 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 registration were drawn in the same manner from the second and third draft lottery, 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 due to the WWI draft. To investigate this, I create a new matched inventor-firm data using a PATSTAT database provided by European Patent Office (2017) that contains 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, 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 inventors that were geographically close to the firm, I need to know where inventors were living when the WWI draft occurred and where the firms were located. I use data from Doran and Yoon (2019) in which patent data are 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 1920 Census, 43 percent of the U.S. population was had a unique first name, middle name, and last name combination. To increase the probability that the fuzzy matching procedure is precise, we only consider the population with a unique name between the ages of 18 and 80 (Doran and Yoon, 2019). I also only consider 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 the 1920 Census lived at the same place between the years 1917 and 1918 when the WWI draft 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 location in the HistPat database.

The data linked to the census provides the age and location of inventors. By constructing this novel linked data, I thus identify which firms worked with which inventors at which ages, where firms and individual inventors were located, and when and in what field inventors filed a patent application.

I use the platform FamilySearch for collecting records on draft registration and veteran service. FamilySearch publicly shares a large collection of historical records. In particular, I collect information that was 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 information in each registration was slightly different, registrants provided name in full, age in years, home address, date of birth, citizenship status, and occupation or employer's name on their draft registration card. Information on full name and birth date is digitized and publicly available from 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, 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 name and birth year 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 that is 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 full name and birth year 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. Further, 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 not served, or neither registered nor served) could be identified after a matching procedure between the patent database and WWI draft registration and service records. I use these data to create supply shocks of inventors who served in the military. These merged data also allows me to measure the effects of inventors who did not serve on innovation rates of other individual inventors, specifically who registered but did not serve or who neither registered nor served while their peers did serve.

Table 1 provides descriptive statistics for the firm panel data that is used in the empirical analysis. The sample consists of firms which had at least one patent application prior to the

[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.

WWI draft and had no patent applications belonging to the arms industry, including firms that manufactured weapons, ammunition, or explosives. Additionally, war-related patents are not counted as the outcome of the number of patent applications. Specifically, I use the International Patent Classification (IPC) in the patent database to identify which patents belong to the arms industry.[9] There could be characteristics of individual firms that could change how a particular firm experienced the effects of the WWI on innovation rates. For example, firms that produced weapons during WWI could have experienced a large increase in their output and thereby increase their inventions when WWI began or when the U.S. entered the war. To address this issue, I use the sample of firms not related to arms industry and the outcome of patents not related to such industry.

Firms significantly decreased their innovation rates during the WWI draft. Consistent with the sample, USPTO administrative data shows a sharp decline at the time of 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 three distinct categories between the years 1910 and 1918 defined as follows: inventors in collaboration space filed a patent application together with a firm, inventors in geographic space lived in the county where a firm was located, inventors in idea space 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 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 firms encountered as falling into three distinct categories: the network of collaboration, the space of geography,

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

and the space of ideas.

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 $j$ for the pre-WWI period. 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 the information on the service records. In particular, let $P_{jCs}$ be the number of pre-WWI patents between the years 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 due to the WWI draft. The supply shock in collaboration space is used to measure a 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 there is no supply shock 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 a geographic location of firm $j$ and the associated inventors. I track the location of firms at the county level by using the information on the geography of patents from the HistPat that covers patents by the USPTO from 1790 to 1975. To identify the location of 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 the years 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 at the time of 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 the information on the international patent classification (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 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 $S_{jT}$ are firm-specific supply shocks in each of 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 years of experience of firm $j$ as years after firm $j$ had a first patent application. The coefficients of interest are $\beta_1$, $\beta_3$ and $\beta_3$, indicating how supply shocks of inventors in collaboration space, geographic space, and idea space affect firm outcomes, respectively.

In the next subsection, I account for the possible endogeneity issues when unobserved characteristics would affect 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 firms that lost many inventors and firms that lost few inventors 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 served were drafted. Therefore, the majority of inventors who were 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. Further, those who were drafted could evade the draft, fail physical examination, or claim exemption during 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 registered and served were involuntarily drafted and inducted into the military due to the WWI draft could be weakened. For example, if inventors who 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 18-45. 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 registration, where young men were disproportionately likely to register. Further, men aged 21-30 were less likely to fail physical examination 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 5 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 who were between the ages of 21 and 30 within given firms, and given 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 the years 1910 and 1916 by inventors aged 21-30 at risk of being drafted and let $P_{jC}$ be 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 at the time of the WWI draft. The difference is that the age profile of inventors is used instead of the military service record of 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 patent 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 21-30, 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 two groups of firms using each of the instruments that measure supply shocks. Firms with many peers at risk of being served have values that are above the median, while firms with few peers have values that are 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 firm's innovation rates 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, $S_{jC}^{*}, S_{jG}^{*}, S_{jF}^{*}$, 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 innovation rates of firms at the year $t$ relative to the omitted base year 1916, the year before the WWI draft registrations and lotteries began in 1917.

In the next section, I will report the results of this analysis.

# 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 3 illustrates the raw data on the number of patents by two types of firms. Figure 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 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 4 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 there are no differential pre-trends between firms. Consistent with the results of Figure 3, estimates shown in Figure 4 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 respectively is presented in the first three columns. The last three columns show the coefficients when three instruments are included at the same time in 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 supply shock in collaboration space, but correlation coefficient is relatively small. The pairwise correlations between the three instruments range from 0.003 to 0.015. The multivariate F test of excluded instruments produces high F statistics, indicating $p$ values that are close to zero. Firms with many inventors at risk decreased the number of inventors in all three spaces during 1917 and 1918. This indicates that firms with a large portion of draftable inventors were more likely to lose inventors at the time of the WWI draft. For example, the estimated coefficient in collaboration space suggests that a 10 percent supply shock of inventors of draftable age group 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. i.e., 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 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 which had at least one patent application prior to the WWI draft and no patent applications within fields that include arms industries such as weapons, ammunition, and explosives. The dependent variable is the number of patent applications not belonging to the arms industries.

I find that the supply shock in collaboration space has a negative effect on innovation rates of firms while the supply shock in idea space has a positive effect. I also find a positive,

[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.

[11] The second-stage regression equation is

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

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, i.e., 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), losing a 10 percent of team members who served reduces patent applications by a 12 percent. Losing a 10 percent of inventors in idea space increases the number of patents annually by 0.01262 (column 4) associated with a 8 percent increase in the number of patents. This suggests that a firm increases its innovation rates if the firm loses inventors outside the firm working in the same industry.

The overall effects are shown in the first panel of Table 3 and I now consider that the relative strength of these effects can vary depending on how close firms are to the knowledge frontiers. For example, some firms close to knowledge frontiers could be more innovative and productive when they lose inventors in idea space because there is less competition within a field, but other firms could be less innovative because they depend heavily on knowledge spillovers. To investigate this, I make 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 that had the number 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 decrease in patents, but it's insignificant. Interestingly, the supply shock in idea space has a significantly negative effect on innovation rates of less innovation 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 a 8 percent decrease in patent applications. Highly innovative firms benefits from the loss of inventors in the space of ideas, but less innovative firms suffers from the loss of inventors in the industry who generate knowledge spillovers.

This provides evidence that firms close to knowledge frontiers create new ideas when there is less competition in idea space, but less innovative firms depends heavily on knowledge spillovers in the space of ideas.

I report 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 instruments $(S^*_{jC}, S^*_{jG}, S^*_{jF})$, respectively.[12] The parameters of interest measure the effect of losing 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. These effects are driven by more innovative firms and 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 innovation rates of firms. I investigate whether the effect of the supply shocks of losing 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 period. In Table A.3, the reduced form estimates are reported relying on the different pre- and post-treatment years. I also report the subsamples of more innovative firms 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 innovation rates of firms in the long term, as result that is not consistent 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. It should be noted that the results in the long run are less precisely measured because of the possibility that firms might change the company name or location over time. To address this issue, I explore the industry level of analysis in

[12]The reduced form regression equation is

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

the mechanism.

In the next subsection, I estimate a number of robustness checks to provide the validity of the instrument and the sensitivity of the results.

## 5.2 Robustness of results

### 5.2.1 Validity of the instrument

The validity of the IV estimates rely on the consistency of innovation rates in the absence of the WWI draft between firms with and without draftable inventors. Specifically, the outcome of firms more exposed to inventors in draftable age group and the outcome of firms less exposed to inventors in draftable age group do not change differently in the absence of the shock, and the shock to the labor supply of inventors in draftable age group 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 31-45 registered in the third draft registration but rarely served. Further, inventors aged 46 or above were not required to register, thus they were not draftable inventors. This would suggest that there should be no relationship between placebo supply shocks of less draftable of 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, the instruments, and supply shocks of served inventors. The correlation between each supply shock of different age groups corresponding to the actual supply shock of inventors who served in each space shows that these two variables are substantially correlated. However, placebo supply shocks within panel B and C are not significantly correlated with 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. Further, 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 firms did not lose those inventors in 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 that there is no evidence of any reduced-form relationship between placebo supply shocks and innovation rates of firms. I also find no relationship 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 innovation rates of firms differently. I provide evidence on common pre-trends between firms shown in Figure 4, 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 placebo draft year. I do not observe any evidence of significant impacts of supply shocks on inventions in each prior year, demonstrating that 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 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. Another possibility is that firms which closely worked with the government were differently affected by such supply shocks. The firms would increase inventions if the government supported or invested in these firms when the U.S. 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 21-30 years old. This leads to biased results.

To address these concerns, I identify which firms and which patents are related to the government. I then use the sample of firms that had no patent applications joint with the government prior to the WWI draft. I also use the outcome of patents not assigned to the government. I find that the results are similar to 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 the relationship to the arms industry. I find that the results are robust reported in Table B.8 using the reduced form.

I directly measure the differential effects of supply shocks on 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 increased their innovation rates when they lost inventors in idea space, while less innovative firms decreased innovation rates in response to such supply shock.

The counts of patents include 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 inventors. In the modified supply shock, I consider how close the firm and inventors are and inventor productivity. I use the number of patents between the years 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 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

[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). Even though I use the *ppml* command to address this problem, as suggested by Santos Silva and Tenreyro (2011), the regression does not produce the results due to a large number of observations with a fixed effect.

and idea space with supply shocks measured by inventors who were not a team member. 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 three spaces. i.e., supply shock in collaboration space for 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 supply shocks in geographic space and idea space. Specifically, 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, 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 three shocks simultaneously provides the marginal effect of supply shock while holding other supply shocks fixed, this modified form of supply shocks explicitly excludes inventors inside the firm when 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 in draftable age group in 1910 Census. I measure the effect of the supply shock of all men within geographic space on innovation rates of firms while other two supply shocks in collaboration space and in idea space remain the same. I find that there is no evidence of relationships among the supply shock 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 innovation rates of firms located in the same county. However, it should be noted that it is not identified which firms they work for.

Finally, I only consider inventors not working with any firm once measuring the effects of losing inventors working in the same geographical location and losing inventors working in the same industry. This analysis allows me to explicitly compare negative competition effects with knowledge spillovers in geographic space and in idea space respectively, because inventors work alone as a freelancer 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, losing a 10 percent of inventors not working with any firm but working in the same industry increases the firm's innovation rate by a 5 percent. It is clear that this effect is driven by negative competition effects in the industry because the loss of inventors does not directly affect firms. This suggest that firms take a chance to be more innovative when potential competitors in the field disappear and negative competition effects dominate knowledge spillovers in the space of idea.

In the next section, I discuss possible drivers and channels of innovation spillover.

# VI Mechanism

## 6.1 The effect on individuals

Individual inventors as well as firms play a crucial role in creating new ideas and inventions. Because individual 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 individual inventors. Aggregated data on patents by individual inventors do not represent patents by firms, and individual inventors could work as an individual or in a team, or work for a single firm or with several firms. Thus, this analysis seeks to understand the channels through which individual 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 lost peers due to 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.

Table B.17 shows summary statistics for the samples of native inventors who had at least one patent application between 1910 and 1916. Inventors who served in the military were more productive in the number of patents prior to their service even though their inventions substantially decreased during the WWI draft. However, it should be noted that served inventors are used to measure the supply shocks and are therefore not included in the analysis sample. Since men who were drafted and served were more likely to be registered during the first and second registration, inventors who served in the military were young than inventors who did not serve. The age profile has a strong positive impact on innovation rates Bell et al. (2019b). Further, I find there is little difference between the number of patents by inventors who served in the military before the WWI draft and patents of inventors who did not serve but registered between the ages of 21 and 30 during the war.

The supply shock in collaboration space is measured in a similar fashion. Individual $i$ had collaborators who had one or more patent applications with inventor $i$ for the pre-WWI period, 1910-1916. Let $P_{iCs}$ be the number of pre-WWI patent applications per year by inventors who collaborated with individual $i$ and served in the military, and let $P_{iC}$ be the number of pre-WWI patents by collaborators of individual $i$. The collaboration-specific service rate at the individual level is then given as

$$S_{iC} = \frac{P_{iCs}}{P_{iC}} \tag{9}$$

The variable $S_{iC}$ measures the supply shock inventor $i$ faced when they lost their network of collaborators.

I measure the supply shock in geographic space using the information on the 1920 Census merged into the patent data. A person observed in the 1920 Census is assumed to have lived in the same place during the WWI draft. Let $G$ be the county where inventor $i$ lived, then let $P_{Gs}$ be the number of pre-WWI patents by inventors who registered and served in county $G$ geographically close to inventor $i$, and let $P_G$ be the number of pre-WWI patents by inventors in county $G$. The geographic-specific service rate is then given by

$$S_{iG} = \frac{P_{Gs}}{P_G} \tag{10}$$

The variable $S_{iG}$ measures the size of the supply shock where inventor $i$ who lived in county $G$ encountered due to the WWI draft.

Finally, I calculate the supply shock in idea space at the firm level using the field composition of individual $i$. Let $patent_{if}$ be the number of pre-WWI patent applications that inventor $i$ had in field $f$, and $patent_i$ be the total number of pre-WWI patents by inventor $i$. Then, let $P_{fs}$ be the number of pre-WWI patents in field $f$ by inventors who registered and served, and let $P_f$ be the number of pre-WWI patents in field $f$ by inventors. The field-specific service rate, calculated by the field composition of inventor $i$, is defined as

$$S_{iF} = \sum_f \frac{patent_{if}}{patent_i} \frac{P_{fs}}{P_f} \tag{11}$$

The variable $S_{iF}$ measures the supply shock experienced by inventor $i$ when they lost their peers who had a similar field.

I employ analogous difference-in-differences specifications to examine the impact of the supply shocks on innovation rates of inventors who did not serve. Specifically, I use the regression model

$$Y_{it} = \beta_1(S_{iC} \times T_t) + \beta_2(S_{iG} \times T_t) + \beta_3(S_{iF} \times T_t) + \theta X_{it} + \gamma_i + \delta_{st} + \epsilon_{it} \tag{12}$$

where $Y_{it}$ is the number of patents of inventor $i$ in year $t$, $S_{iC}, S_{iG}$, and $S_{iF}$ are person-specific supply shocks in collaboration space, geographic space and idea space, and $T_t$ is a dummy variable indicating WWI draft years 1917 and 1918. I include the quartic of age of inventor $i$ in year $t$, $X_{it}$, individual fixed effects, $\gamma_i$, and state-by-year fixed effects, $\delta_{st}$.

Using this regression model, I find large declines in the number of patent applications per year by inventors who did not serve when those inventors lost their collaborators (Table B.18). The supply shock in idea space has a positive effect on innovation rates of inventors who did not serve. Specifically, a supply shock that 10% of collaborators disappear, which is a 0.1 increase in the WWI service rate in collaborator space, weighted by their pre-WWI patents, decreases the number of patent applications per year by 0.003. Conversely, a 0.1 increase in the service rate in idea space increases the number of patents annually by 0.08. Given the dependent variable mean, when inventors lose 10% of their peers, there is a corresponding 2.2% decrease in innovation rates within collaboration space and a 5% increase in idea space.

I find that the supply shocks affect some inventors who registered but did not serve and other inventors who neither registered nor served differently. For relatively young inventors aged 18 and 45 who registered, the supply shock in a network of collaborators has an insignificant and small effect. Conversely, the supply shock in idea space has substantial positive effects on innovation rates. In particular, a 10% increase in the service rate in idea space results in a 9.5% increase in the number of patent applications per year by inventors who registered but did not serve. Inventors who neither registered nor served do not benefit from the supply shock in idea space. Most of these inventors were aged 46 or older, and experienced a large decline in innovation rates when their collaborators served in the military. Specifically, a 10% increase in the service rate in a network of collaboration decreases the number of patents by inventors who did not register or serve by 3.1%.

To address the possible endogeneity issues, I employ the IV strategy using the instruments that rely on the age profile of inventors. Specifically, I create the analogous supply shocks at the individual level in each of three spaces measured by draftable inventors.

Table B.19 reports the coefficients from the analogous first-stage regressions at the individual level. The regressions support the validity of the instruments that have a strong first-stage. The estimated coefficients on the diagonal demonstrate that the instruments are substantially correlated with the supply shocks measured by inventors who served. The pairwise correlations between the three instruments range from 0.002 to 0.079. The multivariate F test of excluded instruments demonstrated that $p$-values were close to zero.

The IV estimates suggest that losing peers in collaboration spaces has a negative effect on patenting by inventors who did not serve, while the supply shock in idea space has a positive but less significant effect compared to the OSL estimates (Table B.20). Specifically, losing 10% of collaborators decreases the number of patent applications per year by 0.007, or 4.5% given the average number of patents.

The supply shock in collaboration space has a negative effect on innovation rates of inventors aged 18 and 45 who registered but did not serve. However, the supply shock in idea space has a strong positive impact on innovation rates. Specifically, a 10% supply shock in idea space increases patenting by inventors who registered but did not serve by 6.9%. The supply shock in collaboration space has a significantly negative effect on innovation rates of inventors who neither registered nor served and were aged 46 or above. A 10% supply shock in collaboration space decreases the number of patents by neither registered nor served inventors by 8.4%. I also consider the reduced form specifications and find that the results are robust to all outcomes reported in Table B.21.

Overall, the results here demonstrate that innovation rates of individual inventors who did not serve were negatively impacted when they lost peers in their collaboration spaces. Individual inventors and entire firms experience a large decline in their inventions when they lose their team members. I find that individual inventors benefit from the supply shock in idea space less than firms. Firms substantially increase their innovation rates when they lose potential competitors in idea space, but individual inventors gain less benefits from losing peers in the space of ideas. I also find that the supply shock in idea space has a strong positive effect on 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 provide evidence that the position of knowledge producers relative to the frontier in its field plays a role in explaining peer effects when they lose peers.

In the next subsection, I explore the industry level analysis.

## 6.2 The effect on new entrants and industry

It is important to understand the long-run impact on innovations and growth, but it is problematic to use the firm panel data measuring in the long-run impact because the firm could change their 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 a 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

$$Y_{it} = \beta(S_i^* \times T_t) + \gamma_i + \delta_t + \epsilon_{it} \tag{13}$$

where $Y_{it}$ is the number of new inventors, new firms, or patent applications for industry $i$ in year $t$. The variable of $S_i^*$ represents the loss of inventors in industry measured by the proportion of inventors in draftable age group 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 lost a 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 an average of entrants to the industry. Because of these new entrants, the industry's overall innovation activity is not significantly affected. I also find these effects persist in the long-run. This implies that the loss of inventors in the industry helps to attract new entrants to the industry, suggesting that an increase in invention by new inventors and firms offsets a decrease in invention due to the loss of inventors.

Another caveat to firm-level analysis is that other firm-level outcomes are not available. To take this caveat into account, 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 which 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 years are available.

In the next subsection, I measure the effect of losing inventors on innovation rates of highly innovative firms.

## 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 the 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 subsamples. Table A.7 reports the reduced form estimates using the subsamples of top innovative firms. I find that firms in the top 5th percentile of inventions decrease their patent applications per year by 0.5824, translating into a 3% decrease when those firms faced a 10% supply shock of team members. Instead, those firms substantially increase innovation rates when they lose their competitors in idea space. Specifically, patent applications increase 7.8% in response to a 10% supply shock in idea space. The results for firms in the top 10th and 25th percentiles are similar to those for firms in the top 5th percentile. The reduced form estimates using the full sample in the same specification reported in Table 4 show that losing 10% of inventors in collaboration space and idea space affect inventions of firms by a 1.3% decrease and 3.9% 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 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 patent by one percentile. The results here suggest that the closer the firms get to knowledge frontiers, the more increase in their patent applications in response to the loss of inventors in the space of ideas.

In the next subsection, I investigate whether the supply shocks affect new ideas and originality of firm's invention.

## 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. There are no significant effects of supply shocks on the number of original patents. 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 as a knowledge frontier create new ideas.

In the next subsection, I estimate the effect of the supply shocks on another measure of innovation: citation-weighted patents.

## 6.5 Citations

It could be assumed that firms would have invested most heavily in the most successful inventions rather than the marginal inventions. To investigate whether the supply shocks affect patents weighted by the later influence of the invention, I reestimate the results in Table 4 with patent citations as the outcome variable. The results are similar in response 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 largely increase citation-weighted patents in the space of ideas, but less innovative firms significantly decrease them. 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.

In the next subsection, I estimate the effect of inventor quality on innovation rates of firms during supply shocks.

## 6.6 Quality of inventors

Firms aim to attract high-skilled workers and productive inventors to encourage innovation and increase productivity. Inventor quality is considered to be one of the key drivers for firm innovation. It is not evident, however, that this positive relationship between inventor quality and firm innovation leads to a causal relationship. 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 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 firms' innovation rates. Interestingly, I find that the supply shock of losing high-quality inventors in geographic space decreases innovation rates of firms, but the supply shock of low-quality inventors increases innovation rates. Thus, the overall effect of losing 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 has large spillovers on geographically close others, but low-quality knowledge producers had a less than proportionate impact. Losing 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 the space of ideas.

In sum, I find evidence of the causal relationship between inventor quality and firm's innovation rates. Losing very high-quality inventors have larger effects on 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 consistent with 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 firm innovation rates. I use a novel approach to this question by creating new matched data and exploiting the new natural experiment of the WWI drafting and subsequent military service of inventors in which firms exogenously lose inventors. I distinguish separate effects of the loss of inventors on a firm's innovation rate. A firm could lose inventor team members due to the WWI military service who worked directly for or with the firm. The firm also could lose inventors close to the firm's location in geographic space (working in the same county) and idea space (working in the same industry).

My analysis revealed four major findings. First, losing inventors who work for a firm itself decreases the firm's innovation rate. Consistent with 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 losing inventors working in the same county does not significantly affect the firm's innovation rate. The quality of inventors provides evidence how the overall effect of losing inventors from the same county is cancelled out. Negative competition effects are enough to offset knowledge spillovers generated by high-quality inventors in geographic space.

Third, I find that losing inventors working in the same industry in which a firm engages increases the firm's innovation rate. This increase suggests that negative competition effects and the law of diminishing returns prevail over knowledge spillovers in the space of ideas. There exists intense competition in the space of ideas, and inventors who are not a team member 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 up when other knowledge producers in the field leave, consistent with Planck's Principle that "new generation grows up when its opponents die."

Fourth, the effects of supply shocks on firm 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 the firms working in the same industry, but less innovative firms decrease innovation rates in response to such supply shock in the space of ideas. This result provides evidence that less innovative firms depend heavily on knowledge spillovers. As inventors in the industry are removed to serve in the military during WWI, the frontier knowledge producers 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 of the evidence presented here pertains to firms' inventions during the early 20th century, a time during which the system of mass production was introduced in the U.S. It is unclear how the findings here might extend to current industries or other areas of knowledge production. In particular, an increase in the mobility of skilled labor may generate large spillovers in 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 network. In contrast, other fields in which researchers tend to work alone and capital equipment is less required may provide more opportunities for new comers to produce new innovation. Therefore, future research should address where new innovations tend to originate.

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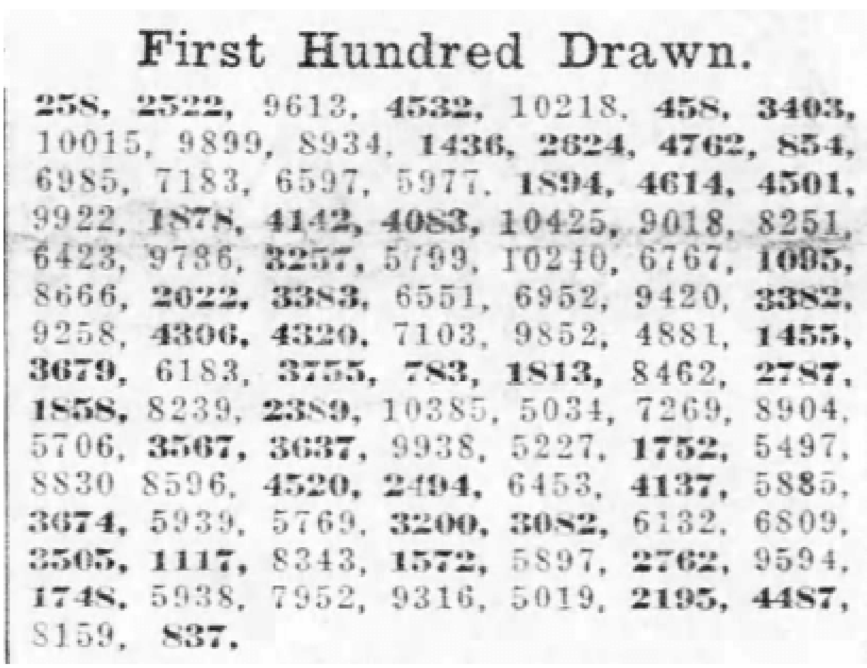
Figure 1: WORLD WAR I DRAFT LOTTERY

(a) The first draft number in the lottery



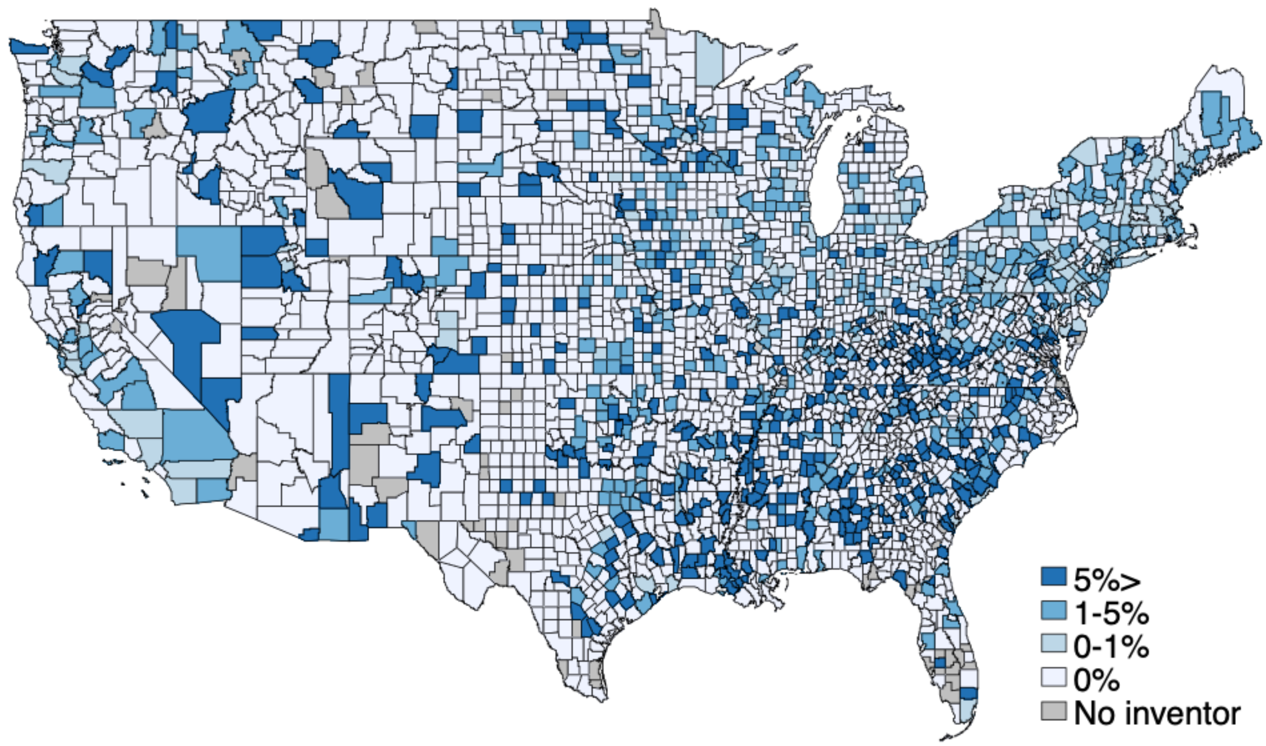
**First Hundred Drawn.**

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, 2622, 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.

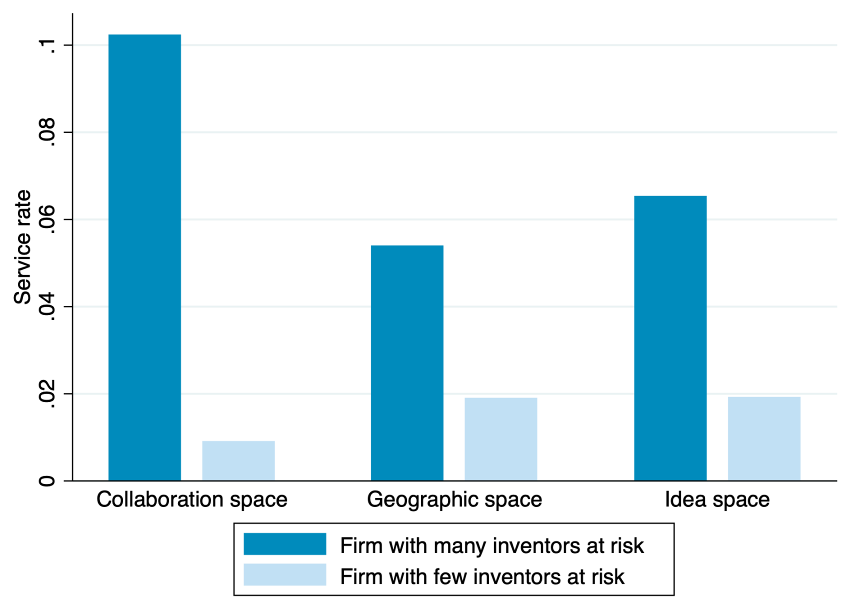
(b) The order of the first hundred numbers drawn

*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



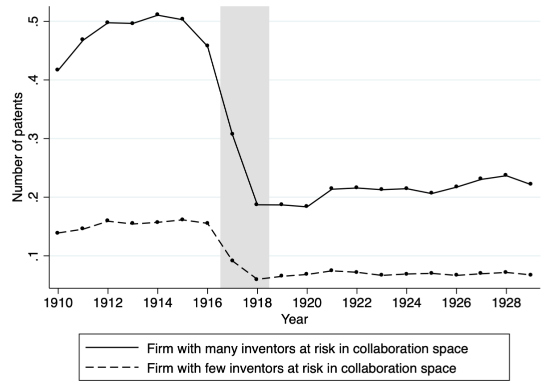

(a) Service rates in county



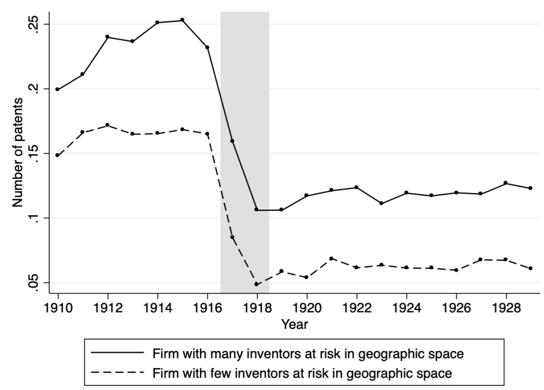

(b) Service rates for firms

*Notes:* The figures show a supply shock of inventors caused by 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 have a portion of inventors in draftable age groups above the median and firms with few inventors at risk which have a portion of inventors in draftable age groups equal to or below the median in each space, respectively.

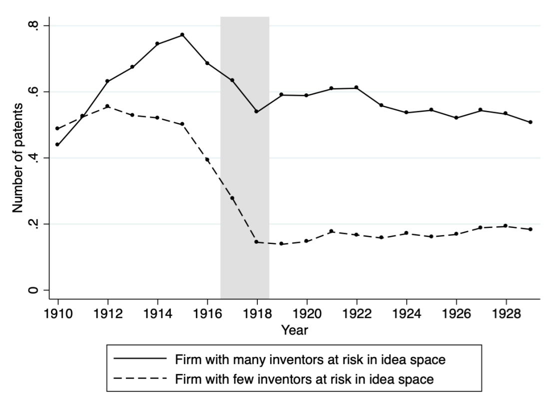
Figure 3: IMPACT OF SUPPLY SHOCK ON INNOVATION RATES




(a) Collaboration space




(b) Geographic space

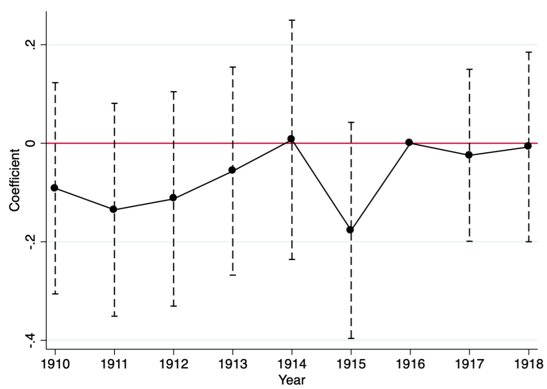



(c) Idea space

*Notes:* The figures show patent applications per year for firms likely to lose inventors and firms unlikely to lose inventors 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. Firms with many inventors at risk have a portion of inventors in draftable age groups above the median, while firms with few inventors have a portion of inventors in draftable age groups equal to or below the median in each space, respectively. 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.

Figure 4: 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 | | | | | |
|---|---|---|---|---|---|---|
| | Collaboration | Geographic | Idea | Collaboration | Geographic | Idea |
| *Instrument* | (1) | (2) | (3) | (4) | (5) | (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 $\beta_1$ | -0.0213*** (0.0077) | – | – | -0.0208*** (0.0077) |
| Geographic space $\beta_2$ | – | 0.0366 (0.0481) | – | 0.0367 (0.0481) |
| Idea space $\beta_3$ | – | – | 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 $\beta_1$ | -0.0370* (0.0217) | – | – | -0.0340 (0.0217) |
| Geographic space $\beta_2$ | – | 0.2322 (0.1627) | – | 0.2303 (0.1624) |
| Idea space $\beta_3$ | – | – | 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 $\beta_1$ | -0.0019 (0.0030) | – | – | -0.0021 (0.0030) |
| Geographic space $\beta_2$ | – | -0.0254 (0.0212) | – | -0.0252 (0.0212) |
| Idea space $\beta_3$ | – | – | -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 SUPPLY SHOCK ON INNOVATION RATES, REDUCED FORM, PLACEBO AGE GROUPS OF INVENTOR

| | 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.

# Appendix

## A.1 Conceptual Framework

The theories of human capital externalities explain how innovations and new ideas generated by knowledge producers or highly-skilled workers influence the productivity of firms. To show these spillovers can coexist with the law of diminishing returns, I develop a modified version of the model following Jones and Romer (2010) and Borjas and Doran (2015a). The production function for invention $Y$ is modeled as an increasing function of the stock of ideas $A$, the stock of resources $K$ such as buildings, land, and machinery, and the stock of inventors $L$. Suppose that the Cobb-Douglas production functions is given by

$$Y = A^{\phi} K^{\alpha} L^{1-\alpha} \tag{14}$$

where $\phi$ is the externalities elasticity for all firms that presents a percent increase in the stock of ideas is associated with a percent increase in invention. The stock of ideas is assumed to be proportional to the number of inventors and dependent on firms $A = L^{\gamma}$ where $\gamma$ measures the firm-specific degree of increasing returns. A marginal product is then given by

$$\text{MPL} = (\gamma\phi + 1 - \alpha) K^{\alpha} L^{\gamma\phi-\alpha} \tag{15}$$

To analyze how the productivity responses to a supply shock, I show that[14]

$$d\text{logMPL} = \alpha d\text{log}K + (\gamma\phi - \alpha) d\text{log}L \tag{16}$$

In the short run, it is assumed that resources $K$ are fixed, $d\text{log}K = 0$, and let $m = d\text{log}L$. The change in innovation rates following a supply shock of inventors is then given by

$$d\text{logMPL} = (\gamma\phi - \alpha) m \tag{17}$$

The equation (17) shows that spillover effects can coexist with competitive effects that are caused by the law of diminishing returns. This model of innovation rates demonstrates that spillovers will increase a firm's innovation rate as a result of increased innovations when

[14] See the mathematical appendix for more details.

the externality's elasticity $\phi$ is large, which leads to $\gamma\phi > \alpha$. On the other hand, the law of diminishing returns will act to decrease firms' innovations arising from the supply shock if the spillover effects are small $\gamma\phi < \alpha$. In the context of the WWI draft, losing inventors could either decrease innovation rates of firms when spillover effects come into play or increase innovation rates when competitors disappear following the law of diminishing returns. This model can also be used to explain the differential effects of the supply shock on invention among firms. In response to losing inventors, a firm would reduce productivity if the firm's degree of increasing returns to the stock of ideas is large $\gamma$, while they would not decrease inventions if a small degree of returns $\gamma$ makes spillovers non-existent.

The degree to which human capital externalities come into play depends on the supply shock in three different spaces. Local externalities within a network of each space allows a generalizable model of the human capital externalities. The production function in equation (14) implies that the supply shock alters the productivity by the same proportion for all firms. It seems plausible, however, that a firm's productivity depends on different externalities in all three spaces. Specifically, the externalities may have a large influence on the firm's innovation rates when the firm loses their inventors who worked for the firm prior to the supply shock. For example, a supply shock of inventors in the same collaboration network would significantly reduce inventions of firms when those inventors lose that network. It is also possible that a supply shock that affects a particular area would have a strong effect on the productivity of firms at that location. Moreover, because patent applications can draw from many fields. For example, a supply shock of inventors in a field of chemistry would have a strong impact on inventions to firms in the chemistry field, but could also impact inventors within related fields.

To illustrate differential effects, I introduce local externalities as the number of efficiency units provided by the total invention workforce. Suppose there are $N$ distinct networks and the generalized workforce is written as

$$L = (A_1^\theta L_1^\beta + \cdots + A_N^\theta L_N^\beta)^{\frac{1}{\beta}} \tag{18}$$

where $A_n$ is the stock of ideas in network $n$, $L_n$ is the stock of invention workforce in network $n$, and $\theta$ is the local externality elasticity. Suppose that the stock of ideas is proportional to the size of invention workforce depending on firms and networks. It is then defined by $A_n = L_n^{\gamma\sigma}$ where $\gamma$ is a firm-specific parameter and $\sigma$ is a network-specific parameter that can vary for each of three spaces. These parameters are used to measure the network-specific spillovers for each firm. The model shows that the change in marginal product for a firm in network $n$ as a result of a supply shock in network $n$ is

$$d\log\text{MPL}_n = (\gamma\phi + 1 - \alpha - \beta)m + (\gamma\sigma\theta + \beta - 1)m_n \tag{19}$$

where $d\log L = m$, $d\log L_n = m_n$, and resources $K$ are fixed in the short run.

The supply shock is therefore measured by the percent change in the total supply of inventors and the percent change in the supply of inventors in network $n$. In the generalized model, the relative strengths of the total externalities elasticity $\phi$, the local externalities elasticity $\theta$ in network $n$, and measures of the firm-specific $\gamma$ and network-specific $\sigma$ degree of returns to the stock of ideas will determine the impact of the supply shock in network $n$.

The model described above implies that the short-run impact of the supply shock on invention can be either positive of negative. Further, the model suggests that the supply shock of inventors differentially affects innovation rates of firms depending on the firm's characteristics and on which of the three distinct spaces is considered. The mixed evidence on the spillover effects in empirical studies can therefore be caused by the fact that the studies measure the conceptually different spillovers arising from distinct supply shocks.

To address this issue and test whether the theory is consistent with empirical evidence, I specifically measure the short-run impact of the supply shock in collaboration space, geographic space, and idea space on firm innovation rates. In this case, supply shocks are caused by the WWI draft during 1917-1918 that enlisted inventors into military service. I provide evidence that team members in collaboration space generate knowledge spillovers supporting the theory of human capital externalities, but other inventors outside the firm working on the same topics have a negative impact on firm's innovation rates supporting the law of diminishing returns in the space of ideas.

## A.2 Data Description

### Patent data

I use PATSTAT to create the firm panel data. I restrict data to "COMPANY" in an indicator of *psn_sector* from the database and "U.S." in *appln_auth*. I then build different measures of patent counts and variables as below.

**Patent applications**: I sum over the patent applications field by a firm each year.

**Original patent applications**: I create an indicator of new words in each patent title from *appln_title*. I assume 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 define original patents applications containing at least one new word that had not already appeared in previous patent titles.

**Patent citations**: I sum over the patent citations by a firm each year using *nb_citing_docdb_fam*

**Location**: To find the location of a firm, I match patents from PATSTAT with the HistPAT database (Petralia et al., 2016). HistPAT provides the county-level geography of patents by the USPTO from 1790 to 1975. I calculate the number of the reported locations of each firm's patents between 1900 and 1916. The most frequently reported location is taken as a proxy for the location. The recent location is used if the number of the reported different locations is equal.

**Year of experience**: I define years of experience of a firm as years after a first patent application filed by the firm. For example, year of experience takes 1 in year 1913 if a first patent is filed in year 1913. Then, year of experience takes 0 before 1913 and is being added each year after 1913 (i.e., 1 in 1913, 2 in 1914, 3 in 1915, ...).

### Inventor data

I use data from Doran and Yoon (2019) in which individual inventors from PATSTAT are merged into the complete 1920 U.S. Census with the full names of individuals. We implement a fuzzy matching procedure between all individual inventors from PATSTAT with 43 percent of the U.S. population with a unique first name, middle name, and last name combination between the ages of 18 and 80. The further details can be found in Doran and Yoon (2019).

## WWI data

I use the platform FamilySearch for collecting records on the U.S. WWI draft registration and military service of individuals. I match the individual inventors merged in the census with records on FamilySearch. The matching is implemented as below.

1. Donal sample: I restrict inventor data to 121,027 male inventors who had at least one patent application before the draft, 1917.

2. Matching: I match the full name and birth year of inventors merged in the census with the digitized information on the full name and birth year from FamilySearch through the python coding. FamilySearch provides 30,165,145 United States World War I Draft Registration Cards (1917-1918) and 6,931,032 United States Veterans Administration Master Index (1917-1940).

3. Filtering: Similarity scores are computed and I keep 95 percent of matching scores.

Using this method, I find 67,342 inventors registered for the draft card and 1,783 inventors served in the military.

## Supply shocks

**Collaboration space**: I use the information on patent applications from PATSTAT to identify which inventors file patent applications joint with which firms at which year. Inventors in collaboration space have patents with a firm before the draft (i.e., inventors working with the firm as a team member).

**Geographic space**: I use the county-level geography of firms matched with the HistPat database and individuals matched with the 1920 Census. Inventors in geographic space work in the same county where a firm is located.

**Idea space**: I use PATSTAT to assign patents to each industry. Specifically, I assign patents to 84 industries (two-digit NACE Rev. 2) via the International Patent Classification (IPC). Inventors in idea space have patents within a particular field in which a firm holds patents (i.e., inventors working in the same industry or working on the same topics in the space of idea).

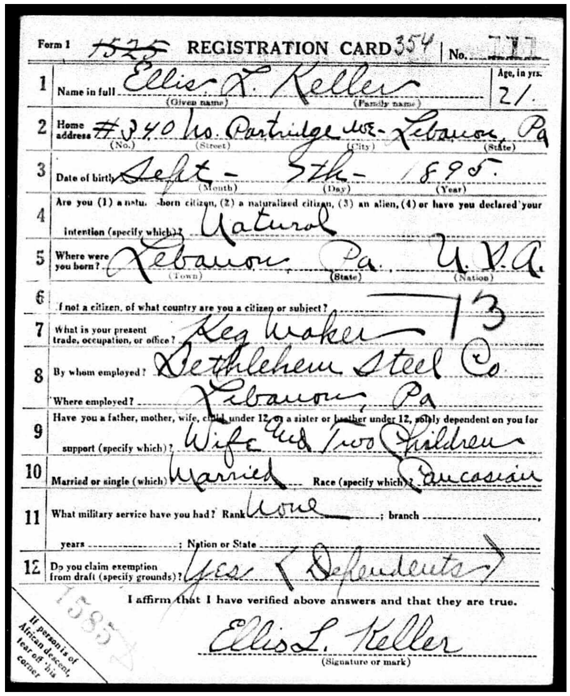
Figure A.1: WORLD WAR I LABOR FORCE


(a) Persons engaged in military, percentage of total labor force


(b) Persons engaged in military (thousands)

*Notes:* The figures show persons engaged in military across the years from administrative data (Kendrick, 1961).

Figure A.2: EXAMPLE OF DRAFT REGISTRATION CARD



Form 1 ~~1525~~ REGISTRATION CARD 354 No. 111

1 Name in full Ellis L. Keller (Given name) (Family name) Age, in yrs. 21.

2 Home address #340 No. Partridge Ave. Lebanon, Pa (No.) (Street) (City) (State)

3 Date of birth Sept. 5th 1895 (Month) (Day) (Year)

4 Are you (1) a natural-born citizen, (2) a naturalized citizen, (3) an alien, (4) or have you declared your intention (specify which)? Natural

5 Where were you born? Lebanon, Pa. U.S.A. (Town) (State) (Nation)

6 If not a citizen, of what country are you a citizen or subject? 13

7 What is your present trade, occupation, or office? Keg Maker

8 By whom employed? Bethlehem Steel Co. Where employed? Lebanon, Pa

9 Have you a father, mother, wife, child under 12, or a sister or brother under 12, solely dependent on you for support (specify which)? Wife and Two Children

10 Married or single (which)? Married Race (specify which)? Caucasian

11 What military service have you had? Rank None; branch; years; Nation or State

12 Do you claim exemption from draft (specify grounds)? Yes (Dependents)

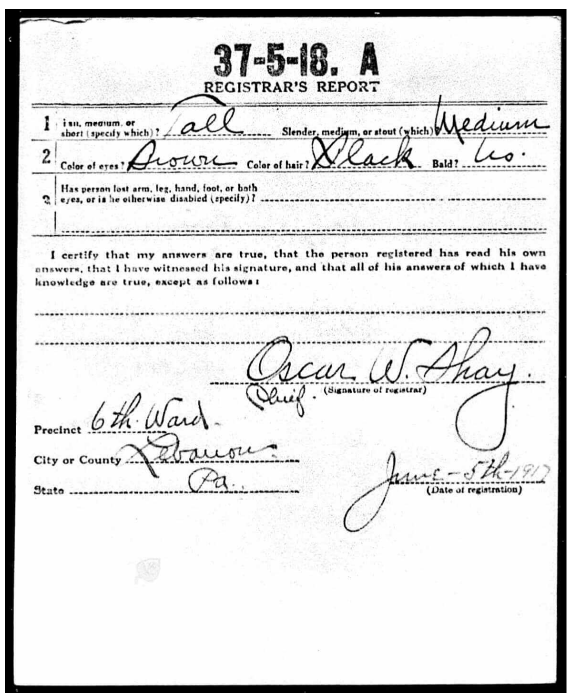
I affirm that I have verified above answers and that they are true.

Ellis L. Keller (Signature or mark)

If person is of African descent, tear off this corner.

1585

(a) Front of the draft registration card



37-5-18. A

REGISTRAR'S REPORT

1 Tall, medium, or short (specify which)? Tall Slender, medium, or stout (which)? Medium

2 Color of eyes? Brown Color of hair? Black Bald? No.

3 Has person lost arm, leg, hand, foot, or both eyes, or is he otherwise disabled (specify)?

I certify that my answers are true, that the person registered has read his own answers, that I have witnessed his signature, and that all of his answers of which I have knowledge are true, except as follows:

Oscar W. Shay. Chief. (Signature of registrar)

Precinct 6th Ward.

City or County Lebanon

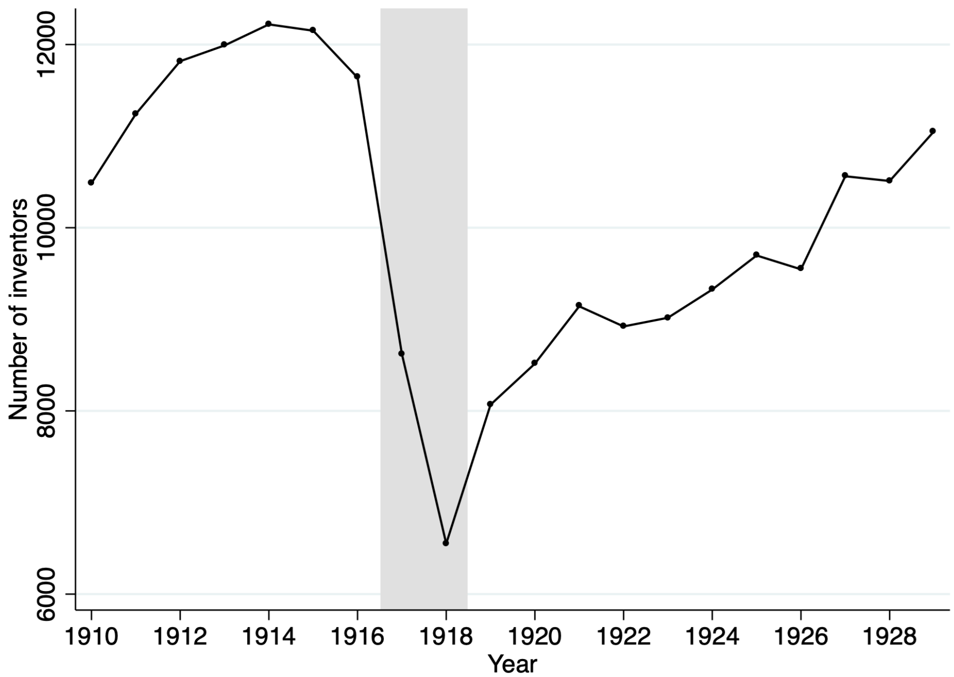
State Pa.

June 5th 1917 (Date of registration)

(b) Back of the draft registration card

*Notes:* This figure shows an example of a draft registration card that was registered in the first registration on June 5, 1917.

Figure A.3: ACTIVE INVENTORS




*Notes:* The figure shows the number of inventors who had at least one patent application given a year.

Table A.1: WORLD WAR I DRAFT

| Register | Draft | Serve | Number | Percent | | | Patent data |
|---|---|---|---|---|---|---|---|
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) |
| Y | Y | Y | 2,566,748 | 58.66 | 11.6 | 91.33 | Served inventor (1,783) |
| Y | N | Y | 243,548 | | | 8.67 | |
| Y | Y | N | 367,200 | - | 88.4 | 1.52 | Registered, but not served (67,342) |
| Y | N | N | 21,423,725 | - | | 98.48 | |
| N | N | Y | 1,980,876 | 41.34 | - | - | - |
| N | N | N | 25,314,807 | - | - | - | Not registered, not served (51,902) |

*Notes:* Administrative data from U.S. Provost Marshal General (1919) provides the numbers in column (4). The numbers in parenthesis in column (8) present the number of inventors who had at least one patent application prior to the WWI draft.

Table A.2: IMPACT OF SUPPLY SHOCK ON INNOVATION RATES, OLS COEFFICIENTS

| | Specification | | | |
|---|---|---|---|---|
| | (1) | (2) | (3) | (4) |
| *Dependent variable: Patent applications per year* | | | | |
| *A. Firms* | | | | |
| Supply shock in Collaboration space | -0.0271<br>(0.0175) | – | – | -0.0282<br>(0.0176) |
| Geographic space | – | 0.0449<br>(0.0745) | – | 0.0448<br>(0.0745) |
| Idea space | – | – | 0.0953*<br>(0.0574) | 0.0963*<br>(0.0575) |
| Dependent variable mean | 0.1618 | | | |
| Number of observations | 261,279 | | | |
| Number of firms | 29,031 | | | |
| *B. More innovative firms* | | | | |
| Supply shock in Collaboration space | -0.0433<br>(0.0487) | – | – | -0.0463<br>(0.0491) |
| Geographic space | – | 0.3347<br>(0.2687) | – | 0.3380<br>(0.2689) |
| Idea space | – | – | 0.2065*<br>(0.1246) | 0.2084*<br>(0.1247) |
| Dependent variable mean | 0.3481 | | | |
| Number of observations | 81,837 | | | |
| Number of firms | 9,093 | | | |
| *C. Less innovative firms* | | | | |
| Supply shock in Collaboration space | -0.0111<br>(0.0071) | – | – | -0.0105<br>(0.0071) |
| Geographic space | – | -0.0372<br>(0.0328) | – | -0.0366<br>(0.0327) |
| Idea space | – | – | -0.0661***<br>(0.0200) | -0.0658***<br>(0.0200) |
| 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 A.3: LONG-RUN IMPACT OF SUPPLY SHOCK ON INNOVATION RATES, REDUCED FORM

| | Specification | | | |
|---|---|---|---|---|
| | (1) | (2) | (3) | (4) |
| *Dependent variable: Patent applications per year* | | | | |
| *A. Year: 1910-1929, Post-treatment years: 1917-1929* | | | | |
| Supply shock in Collaboration space | -0.0257*** (0.0051) | – | – | -0.0254*** (0.0051) |
| Geographic space | – | -0.1548*** (0.0340) | – | -0.1532*** (0.0339) |
| Idea space | – | – | 0.0078 (0.0178) | 0.0063 (0.0178) |
| Dependent variable mean | 0.1618 | | | |
| Number of observations | 580,620 | | | |
| Number of firms | 29,031 | | | |
| *B. Year: 1910-1950, Post-treatment years: 1917-1950* | | | | |
| Supply shock in Collaboration space | -0.0311*** (0.0050) | – | – | -0.0316*** (0.0050) |
| Geographic space | – | -0.1857*** (0.0347) | – | -0.1827*** (0.0346) |
| Idea space | – | – | -0.0910*** (0.0134) | -0.0929*** (0.0134) |
| Dependent variable mean | 0.1618 | | | |
| Number of observations | 1,190,271 | | | |
| Number of firms | 29,031 | | | |
| *C. Year: 1900-1950, Post-treatment years: 1917-1950* | | | | |
| Supply shock in Collaboration space | -0.0265*** (0.0033) | – | – | -0.0266*** (0.0033) |
| Geographic space | – | -0.1375*** (0.0232) | – | -0.1354*** (0.0231) |
| Idea space | – | – | -0.0315*** (0.0087) | -0.0330*** (0.0087) |
| Dependent variable mean | 0.1444 | | | |
| Number of observations | 1,480,581 | | | |
| 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.

Table A.4: IMPACT OF SUPPLY SHOCK ON INNOVATION RATES, PLACEBO WWI DRAFT YEARS

| | Specification | | | |
|---|---|---|---|---|
| | (1) | (2) | (3) | (4) |
| *Dependent variable: Patent applications per year* | | | | |
| *A. Placebo pre-treatment years (1910) and post-treatment years (1911-1916)* | | | | |
| Supply shock in Collaboration space | -0.0279<br>(0.0284) | – | – | -0.0259<br>(0.0288) |
| Geographic space | – | -0.0703<br>(0.1174) | – | -0.0505<br>(0.1187) |
| Idea space | – | – | 0.0073<br>(0.0648) | 0.0064<br>(0.0649) |
| *B. Placebo pre-treatment years (1910-1911) and post-treatment years (1912-1916)* | | | | |
| Supply shock in Collaboration space | -0.0071<br>(0.0241) | – | – | -0.0007<br>(0.0244) |
| Geographic space | – | -0.1393<br>(0.1038) | – | -0.1384<br>(0.1054) |
| Idea space | – | – | 0.0754<br>(0.0608) | 0.0753<br>(0.0608) |
| *C. Placebo pre-treatment years (1910-1912) and post-treatment years (1913-1916)* | | | | |
| Supply shock in Collaboration space | -0.0120<br>(0.0223) | – | – | -0.0089<br>(0.0225) |
| Geographic space | – | -0.0644<br>(0.0983) | – | -0.0573<br>(0.0993) |
| Idea space | – | – | 0.0666<br>(0.0601) | 0.0662<br>(0.0601) |
| *D. Placebo pre-treatment years (1910-1913) and post-treatment years (1914-1916)* | | | | |
| Supply shock in Collaboration space | 0.0278<br>(0.0220) | – | – | 0.0313<br>(0.0222) |
| Geographic space | – | -0.0357<br>(0.0910) | – | -0.0590<br>(0.0920) |
| Idea space | – | – | 0.0888<br>(0.0599) | 0.0899<br>(0.0599) |

*Notes:* The sample consists of firms which had at least one patent application prior to the WWI draft. The outcome variable is the number of patent applications per year. The number of patent applications is winsorized at 10. Standard errors are clustered by firms.

Table A.5: IMPACT OF SUPPLY SHOCK ON INNOVATION RATES, REDUCED FORM, CONTROLLING FOR THE GOVERNMENT'S EFFECT

| | Specification | | | |
|---|---|---|---|---|
| | (1) | (2) | (3) | (4) |
| *Dependent variable: Patent applications per year* | | | | |
| *A. Firms* | | | | |
| Supply shock in Collaboration space | -0.0219*** (0.0067) | – | – | -0.0215*** (0.0067) |
| Geographic space | – | -0.0611 (0.0430) | – | -0.0602 (0.0429) |
| Idea space | – | – | 0.0590* (0.0343) | 0.0579* (0.0343) |
| Dependent variable mean | 0.1617 | | | |
| Number of observations | 260,901 | | | |
| Number of firms | 28,989 | | | |
| *B. More innovative firms* | | | | |
| Supply shock in Collaboration space | -0.0372* (0.0205) | – | – | -0.0351* (0.0205) |
| Geographic space | – | 0.1413 (0.1444) | – | 0.1383 (0.1444) |
| Idea space | – | – | 0.1502* (0.0869) | 0.1468* (0.0870) |
| Dependent variable mean | 0.3484 | | | |
| Number of observations | 81,567 | | | |
| Number of firms | 9,063 | | | |
| *C. Less innovative firms* | | | | |
| Supply shock in Collaboration space | -0.0029 (0.0027) | – | – | -0.0030 (0.0027) |
| Geographic space | – | -0.0315* (0.0190) | – | -0.0310 (0.0190) |
| Idea space | – | – | -0.0423*** (0.0127) | -0.0424*** (0.0127) |
| Dependent variable mean | 0.0768 | | | |
| Number of observations | 179,334 | | | |
| Number of firms | 19,926 | | | |

*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 and for which firms collaborated with the government. 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 and the government. The number of patent applications is winsorized at 10. Standard errors are clustered by firms.

Table A.6: IMPACT OF SUPPLY SHOCK ON NEW INVENTORS, NEW FIRMS, AND INNOVATION AT THE INDUSTRY-LEVEL, REDUCED FORM

| | Dependent variable | | |
|---|---|---|---|
| | New inventors (1) | New firms (2) | Patents (3) |
| *A. Year: 1910-1918, Post-treatment years: 1917-1918* | | | |
| Supply shock × Post-treatment | 471* | 55* | 0.2426 |
| | (251) | (30) | (1.0670) |
| Dependent variable mean | 190 | 26 | 4.7298 |
| Number of observations | 756 | 756 | 756 |
| *B. Year: 1910-1929, Post-treatment years: 1917-1929* | | | |
| Supply shock × Post-treatment | 1388* | 113* | -0.2416 |
| | (758) | (64) | (1.3223) |
| Dependent variable mean | 190 | 26 | 4.7298 |
| Number of observations | 1,680 | 1,680 | 1,680 |
| *C. Year: 1900-1929, Post-treatment years: 1917-1929* | | | |
| Supply shock × Post-treatment | 1431* | 120* | 0.4187 |
| | (773) | (67) | (1.3543) |
| Dependent variable mean | 563 | 55 | 5.8460 |
| Number of observations | 2,520 | 2,520 | 2,520 |
| *D. Year: 1900-1950, Post-treatment years: 1917-1950* | | | |
| Supply shock × Post-treatment | 1254** | 105* | 0.4062 |
| | (617) | (56) | (1.2525) |
| Dependent variable mean | 563 | 55 | 5.8460 |
| Number of observations | 4,284 | 4,284 | 4,284 |
| Number of industries | 84 | 84 | 84 |

*Notes:* New inventors are those who patent for the first time in the industry, defined at the level of 84 industry classes in the PATSTAT database. New firms are new entrant firms which patent for the first time in the industry. The dependent variable of patents are the number of patent applications per year at the industry level, taken in natural logarithms. Standard errors are clustered by industries.

Table A.7: IMPACT OF SUPPLY SHOCK ON INNOVATION RATES, REDUCED FORM, HIGHLY INNOVATIVE FIRM

| | Specification | | | |
|---|---|---|---|---|
| | (1) | (2) | (3) | (4) |
| *Dependent variable: Patent applications per year* | | | | |
| *A. Firms in the top 5 percentile of pre-WWI patents* | | | | |
| Supply shock in Collaboration space | -0.6461*** (0.1839) | – | – | -0.5824*** (0.1816) |
| Geographic space | – | 1.6473 (2.0079) | – | 1.1058 (1.9774) |
| Idea space | – | – | 1.5834*** (0.3360) | 1.4985*** (0.3362) |
| Dependent variable mean | 1.9227 | | | |
| Number of observations | 12,447 | | | |
| Number of firms | 1,383 | | | |
| *B. Firms in the top 10 percentile of pre-WWI patents* | | | | |
| Supply shock in Collaboration space | -0.4037*** (0.1043) | – | – | -0.3666*** (0.1032) |
| Geographic space | – | 0.5951 (0.9502) | – | 0.4793 (0.9336) |
| Idea space | – | – | 1.3563*** (0.2374) | 1.3143*** (0.2374) |
| Dependent variable mean | 1.2970 | | | |
| Number of observations | 26,397 | | | |
| Number of firms | 2,933 | | | |
| *C. Firms in the top 25 percentile of pre-WWI patents* | | | | |
| Supply shock in Collaboration space | -0.2066*** (0.0414) | – | – | -0.1909*** (0.0412) |
| Geographic space | – | 0.3260 (0.3088) | – | 0.2528 (0.3066) |
| Idea space | – | – | 0.8679*** (0.1446) | 0.8469*** (0.1445) |
| Dependent variable mean | 0.6663 | | | |
| Number of observations | 73,314 | | | |
| Number of firms | 8,146 | | | |

*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.

Table A.8: IMPACT OF SUPPLY SHOCK ON ORIGINAL PATENT APPLICATIONS, REDUCED FORM

| | Specification | | | |
|---|---|---|---|---|
| | (1) | (2) | (3) | (4) |
| *Dependent variable: Original patent applications per year* | | | | |
| *A. Firms* | | | | |
| Supply shock in Collaboration space | 0.0020 (0.0020) | – | – | 0.0021 (0.0019) |
| Geographic space | – | 0.0007 (0.0121) | – | 0.0004 (0.0121) |
| Idea space | – | – | 0.0112 (0.0089) | 0.0113 (0.0089) |
| Dependent variable mean | 0.0190 | | | |
| Number of observations | 261,279 | | | |
| Number of firms | 29,031 | | | |
| *B. More innovative firms* | | | | |
| Supply shock in Collaboration space | 0.0037 (0.0059) | – | – | 0.0040 (0.0059) |
| Geographic space | – | 0.0309 (0.0376) | – | 0.0313 (0.0377) |
| Idea space | – | – | 0.0200 (0.0227) | 0.0205 (0.0227) |
| Dependent variable mean | 0.0403 | | | |
| Number of observations | 81,837 | | | |
| Number of firms | 9,093 | | | |
| *C. Less innovative firms* | | | | |
| Supply shock in Collaboration space | 0.0025** (0.0011) | – | – | 0.0025** (0.0011) |
| Geographic space | – | 0.0005 (0.0097) | – | 0.0003 (0.0096) |
| Idea space | – | – | -0.0002 (0.0051) | -0.0001 (0.0051) |
| Dependent variable mean | 0.0093 | | | |
| 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 original patent applications per year defined as patents with new one/two/three word phrases in patent title that did not exist in previous patent titles. The number of patent applications is winsorized at 10. Standard errors are clustered by firms.

Table A.9: IMPACT OF SUPPLY SHOCK ON PATENT CITATIONS, REDUCED FORM

| | Specification | | | |
|---|---|---|---|---|
| | (1) | (2) | (3) | (4) |
| *Dependent variable: Patent citations per year* | | | | |
| *A. Firms* | | | | |
| Supply shock in Collaboration space | -0.0360** (0.0157) | – | – | -0.0352** (0.0157) |
| Geographic space | – | -0.1424 (0.1068) | – | -0.1412 (0.1067) |
| Idea space | – | – | 0.1035 (0.0861) | 0.1017 (0.0860) |
| Dependent variable mean | 0.2674 | | | |
| Number of observations | 261,279 | | | |
| Number of firms | 29,031 | | | |
| *B. More innovative firms* | | | | |
| Supply shock in Collaboration space | -0.0686 (0.0466) | – | – | -0.0635 (0.0465) |
| Geographic space | – | 0.0979 (0.3720) | – | 0.0921 (0.3720) |
| Idea space | – | – | 0.3829* (0.2137) | 0.3765* (0.2135) |
| Dependent variable mean | 0.5610 | | | |
| Number of observations | 81,837 | | | |
| Number of firms | 9,093 | | | |
| *C. Less innovative firms* | | | | |
| Supply shock in Collaboration space | -0.0076 (0.0091) | – | – | -0.0082 (0.0091) |
| Geographic space | – | -0.1224** (0.0605) | – | -0.1208** (0.0601) |
| Idea space | – | – | -0.1713*** (0.0430) | -0.1716*** (0.0430) |
| Dependent variable mean | 0.1335 | | | |
| 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 citations. The number of patent citations is winsorized at 20. Standard errors are clustered by firms.

# Mathematical Appendix: Conceptual Framework

$$Y = A^{\phi}K^{\alpha}L^{1-\alpha}$$

Assume $A = L^{\gamma}$ where $\gamma$ is a firm-specific parameter.

$$Y = L^{\gamma\phi}K^{\alpha}L^{1-\alpha} = K^{\alpha}L^{\gamma\phi+1-\alpha}$$

$$\text{MPL} = (\gamma\phi + 1 - \alpha)K^{\alpha}L^{\gamma\phi-\alpha}$$

$$\text{logMPL} = \log(\gamma\phi + 1 - \alpha) + \alpha\text{log}K + (\gamma\phi - \alpha)\text{log}L$$

$$d\text{logMPL} = \alpha d\text{log}K + (\gamma\phi - \alpha)d\text{log}L$$

Assume $d\text{log}K = 0$ in the short run and let $d\text{log}L = m$

$$\Rightarrow \; d\text{logMPL} = (\gamma\phi - \alpha)m$$

Now, assume $L$ is given by

$$L = (A_1^{\theta}L_1^{\beta} + \cdots + A_N^{\theta}L_N^{\beta})^{\frac{1}{\beta}}$$

Assume $A_n = L_n^{\gamma\sigma}$ where $\sigma$ is a network-specific parameter.

$$L = (L_1^{\gamma\sigma\theta+\beta} + \cdots + L_N^{\gamma\sigma\theta+\beta})^{\frac{1}{\beta}}$$

$$Y = A^{\phi}K^{\alpha}L^{1-\alpha} = K^{\alpha}L^{\gamma\phi+1-\alpha}$$

$$= K^{\alpha}(L_1^{\gamma\sigma\theta+\beta} + \cdots + L_N^{\gamma\sigma\theta+\beta})^{\frac{1}{\beta}(\gamma\phi+1-\alpha)}$$

$$\text{MPL}_n = \frac{1}{\beta}(\gamma\phi + 1 - \alpha)K^{\alpha}(L_1^{\gamma\sigma\theta+\beta} + \cdots + L_N^{\gamma\sigma\theta+\beta})^{\frac{1}{\beta}(\gamma\phi+1-\alpha)-1}(\gamma\sigma\theta + \beta)L_n^{\gamma\sigma\theta+\beta-1}$$

$$\text{logMPL}_n = \text{log}\frac{1}{\beta}(\gamma\phi + 1 - \alpha) + \alpha\text{log}K + \left(\frac{1}{\beta}(\gamma\phi + 1 - \alpha) - 1\right)\text{log}L^{\beta}$$
$$+ \log(\gamma\sigma\theta + \beta) + (\gamma\sigma\theta + \beta - 1)\text{log}L_n$$

where $L^{\beta} = L_1^{\gamma\sigma\theta+\beta} + \cdots + L_N^{\gamma\sigma\theta+\beta}$

$$d\text{logMPL}_n = \alpha d\text{log}K + (\gamma\phi + 1 - \alpha - \beta)d\text{log}L + (\gamma\sigma\theta + \beta - 1)d\text{log}L_n$$

Assume $d\text{log}K = 0$ in the short run and let $d\text{log}L = m$, $d\text{log}L_n = m_n$

$$\Rightarrow \; d\text{logMPL}_n = (\gamma\phi + 1 - \alpha - \beta)m + (\gamma\sigma\theta + \beta - 1)m_n$$