Research Policy 54 (2025) 105230

Contents lists available at ScienceDirect

Research Policy

journal homepage: www.elsevier.com/locate/respol

Concept and creativity: Proof-of-concept demonstration and aviation innovation in the United States, 1894–1913☆

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ARTICLE INFO

JEL classification:
D230
L930
M590
N110
O310

Keywords:
Proof-of-concept demonstration
Creativity
Innovation
Technological progress
Aviation
Industry emergence and evolution
Business and economic history

ABSTRACT

This article conceptualizes proof-of-concept demonstration as the public display of a functioning new technology and investigates its effect on technological progress and industry emergence within the context of aviation in the United States between 1894 and 1913. The first successful demonstration of powered flight marked a watershed moment in the development of aviation and provided a proof-of-concept event that would dramatically change the trajectory and locus of flight-focused innovation. Our historical case study of these dynamics indicates that there was a dramatic increase in the amount of aviation patenting following successful public demonstrations of the airplane. We find that the geographic locus of aviation innovation in the United States shifted starting in 1908, the year in which the Wright brothers first publicly demonstrated their early aircraft. After this event, aviation patenting increased most significantly in areas that were geographically near to the demonstration site and in areas with high pre-existing levels of innovative activity. We observe that inventors placed greater focus on new elements of airplanes related to the proof-of-concept design, and we also find an increase in patenting of alternative types of flying devices that were conceptually and technologically distinct from the demonstrated fixed-wing airplane. Ultimately, this work links micro- and macro-levels of analysis and perspectives to provide a comprehensive account of the creative processes that underpin technological advance, and it contributes to our understanding of the incubation stage of industry emergence around new technologies.

1. Introduction

One of the key contributions of the interdisciplinary innovation studies literature has been its role in deepening our understanding of how new technologies develop (e.g., Arthur, 1989; Griliches, 1957; Rosenberg, 1982), underpin industry evolution (e.g., Abernathy and Clark, 1985; Audretsch, 1995; Moeen and Agarwal, 2017), and influence economic outcomes of regions (e.g., Jaffe, 1989; Romer, 1990; Solow, 1957). This stream of research has taught us a great deal about the history of technological progress (e.g., Dosi, 1982; Etzkowitz and Leydesdorff, 2000; Mokyr, 1992), and it has helped explain key differences in the fortunes of firms and geographies over time (e.g., Aschhoff and Sofka, 2009; Audretsch and Feldman, 1996; Nelson, 1993; Stuart and Sorenson, 2003), which have also generated important insights for scholars, managers, and policymakers. In this article, we turn our attention to *proof-of-concept demonstration* as a critical, yet understudied, catalyst influencing the trajectory and locus of innovation during the early stage of an industry's emergence around a new technology.

We conceptualize proof-of-concept demonstration as a display of a functioning new technology to an external audience who disseminates information about its success more widely. Distinct from prototypes or the beta-testing of new commercial applications of technologies (e.g., Audretsch et al., 2012; Bakker et al., 2012; Lu et al., 2019) and later industry dominant designs (e.g., Abernathy and Utterback, 1978; Tushman and Murmann, 1998), proof-of-concept is limited to the early pre-commercialization phase of an industry's emergence—and it designates the point at which the underlying feasibility of a new technology is proven to others to be possible. Thus, proof-of-concept demonstration is an external-facing event that is characterized by a display of the functioning technology for those beyond its inventors and immediate stakeholders. Such displays may be semi-public to the extent that information and evidence regarding the functionality of the technology is made apparent to a more narrow set of actors who then disseminate them through information channels such as the media. Accordingly, proof-of-concept demonstration

☆ This article is part of a special issue entitled: Creativity and Innovation published in Research Policy.

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https://doi.org/10.1016/j.respol.2025.105230
Received 30 November 2023; Received in revised form 5 March 2025; Accepted 7 March 2025

is more than the expression of an abstract idea. It provides a critical concrete juncture in the evolution of a technology, from a hypothetical object to a realized entity, that triggers "a period of technological ferment" (Tushman and Anderson, 1986, p. 440). The fact that such demonstrations of a functioning technology are external-facing means that they can direct the attention of others who had not previously been aware of the state of progress within the technological domain.

There are ample historical and contemporaneous examples of demonstrated technologies that have widely spotlighted progress within their respective domains.[1] Despite the rich literature and extensive body of research on the development of new technologies and innovation (see also Fagerberg et al., 2005; Hall and Rosenberg, 2010), however, there are two critical intertwined gaps in our current understanding about how proof-of-concept demonstration of a new technology shapes subsequent innovation and industry emergence. First, the academic literature on technology development often focuses on later stages of an industry lifecycle (Agarwal et al., 2017). While this may be, in part, due to data availability, it is also the case that researchers in strategy and economics often devote their energies to explaining key value creation and capture outcomes that only begin to manifest when a new technology begins to hit the market or when practical applications for a technology become apparent to firms. However, this leaves out the early stages of a technology's development, one in which the need for individual inventors' creativity and novel thinking are perhaps most critical but relatively less understood. Second, the macro-level economic outcomes examined in research addressing innovation and technological development are inescapably a result of micro-level creative processes that play out at the individual and team level over many years. Understanding broad changes in technology and innovation due to demonstration of proof-of-concept, accordingly, requires that researchers examine both individual innovation and collective-aggregate outcomes together over time in order to better disentangle how trigger events spawn new industries around new technologies (e.g., Aversa et al., 2022a; Moeen et al., 2020). Bringing these levels of analysis together can provide meaningful insight into underlying processes of technological progress and industry evolution.

This article is oriented on the following research question: *How does proof-of-concept demonstration of a new technology shape the intensity of innovative activity?* In addressing this question, there is an inherent opportunity to advance the related literatures on creativity and innovation by considering both the micro-level problem of how heterogeneous local actors respond to the public display of a new technology and the macro-level consequences of such responses on the geography of innovation during the incubation stage of industry emergence. Addressing this can speak to key factors related to technological spillovers by considering proof-of-concept demonstration's effects on innovations in both core and adjacent domains of the focal technology.

We study these issues in the context of technological progress in aviation in the United States during the late 19th and early 20th centuries. Using the Wright brother's public demonstration of powered flight of a heavier-than-air manned airplane[2] as a proof-of-concept shock that potentially altered the creative attention and focus of innovators across the country, our historical case study engages with extensive archival material in order to examine how aviation-related innovation progressed in the subsequent decade. These public proof-of-concept demonstration flights occurred during September 1908 at Fort Myer, Virginia, approximately five years after the Wright's privately-conducted first flight took place in North Carolina. We have constructed a rich body of primary and secondary historical documentation that both helps to contextualize our investigation and also provides a foundation for gaining insight into the behavior of actors that were involved with the development of early flight. Notably, our data include the full corpus of aviation patents granted in the United States between 1894 and 1913, which gives us very granular detail about the innovations that occurred before and after proof-of-concept demonstration and serves as the basis for our quantitative analyses.

This setting is ideal for our research purposes for a variety of reasons. First, airplane proof-of-concept demonstration provided a creative shock that, in 1908, had become recognized throughout the country and world. The success of the airplane provided unambiguous demonstration that powered flight could be achieved, and it influenced the behavior of other potential inventors in pursuit of advancing aviation technologies (Gibbs-Smith, 1960). Hence, early aviation provides a clear setting that maps onto our theoretical foundation. Second, airplane proof-of-concept demonstration occurred well before the commercialization phase of the aviation industry in the United States, which did not take place at scale for civil purposes until after the Post Office Department's establishment of commercial airmail routes during the 1920s and 1930s (Sohn et al., 2024a). Thus, examining this setting will help us to better understand technological development during the incubation stage of industry emergence, which is difficult to investigate in many settings. Finally, the airplane was a revolutionary technology that developed into a critically important industry and fundamentally transformed the world over the subsequent decades (Gibbs-Smith, 1960; see also Bonaccorsi and Giuri, 2000; Bryan, 2023; Frenken, 2000; Hanlon and Jaworski, 2022; Hiatt et al., 2018; Mowery and Rosenberg, 1981). A more complete understanding of the processes underpinning these developments offers us richer insight into issues of significant economic importance.

This work provides both theoretical and empirical contributions to our understanding of proof-of-concept demonstration and its effects on inventor creativity and industry emergence. We achieve this through constructing a historical case study of the development of the airplane and subsequent technological progress in aviation (see also Argyres et al., 2020; Kirsch et al., 2014; Wadhwani et al., 2020). Our abductive "history-to-theory" approach allows us to help lay the groundwork for the emergence of preliminary theoretical insights about a phenomenon weakly explained in current theory (e.g., Bamberger, 2019; Behfar and Okhuysen, 2018; Sætre and Van de Ven, 2021)—in particular, the relationship between demonstration of proof-of-concept and innovative output in nascent technological domains. We engage with extensive archival material and a rich body of prior aviation scholarship to enhance our theoretical understanding of these issues. Empirically, we bridge micro- and macro-levels of analysis and perspectives by structuring our investigation around focused questions that emerge from both theory and data.

Our findings indicate that there was a substantial increase in aviation patenting following the first airplane proof-of-concept demonstrations. This suggests that proof-of-concept demonstration was a key trigger event that activated ideation processes of creative individuals in the pre-commercialization era of the aviation industry's evolution. We also observe that the geographic locus of aviation innovation in the United States changed dramatically after 1908, with aviation patenting increasing most significantly in areas that had high levels of pre-existing innovative activity and in areas that were nearer to the proof-of-concept demonstration site. However, we do not find evidence that being a population center or manufacturing hub corresponded to a distinct

[1] We expand on other examples in more detail in Discussion Section 5.1.

[2] A variety of terminology had been used to describe what later became known as the airplane. Much of it seems anachronistic now (e.g., flying machine). For the sake of brevity, we limit our labelling to 'airplane' when referring to fixed-wing designs and use 'powered flight' or just 'flight' as the primary descriptor for these aviation-related activities. Likewise, throughout the article we use the modern spelling of 'airplane,' rather than 'aeroplane,' etc., unless there is a need to do otherwise to emphasize a specific point or we are quoting/referring to archival source material. We also generally refrain from adding adjectives describing the nature of these airplanes but note that we follow Gibbs-Smith (1960, p. 35) in specifying that this first flight was "first" insofar as the Wrights "were the first men to make powered, sustained and controlled flights in an aeroplane, and land on the ground as high as that from which they took off."

increase in aviation patenting, which suggests that prior innovative experience was uniquely directed towards subsequent innovation. Moreover, while we find a nominal increase in the patenting activity of corporate inventors, innovative output increased more substantially, and the overall magnitude remained much higher for individual inventors compared to firms during this incubation phase. This again indicates that innovation during the pre-commercialization era can be a consequence of individual creativity and outside-the-box thinking that is less influenced by established organizational processes or specialized firm capabilities. With respect to innovative emphasis, our results show that inventors began to address new features of airplanes following the proof-of-concept demonstration, and they also increased their patenting of alternative types of flying devices that were conceptually and technologically distinct from the demonstrated fixed-wing airplane design. This highlights that proof-of-concept can be a key trigger of exploratory creativity, sending a signal about the feasible returns from exploration to the pool of potential inventors, which facilitates subsequent spillover innovations in both core areas and in areas adjacent to that of the demonstrated technology. Our empirical investigation, therefore, offers a comprehensive and dynamic account of the creative processes that underpinned the invention of the airplane and the subsequent innovations that facilitated the eventual emergence of the American aviation industry.

2. Theoretical foundation

In addition to its application to innovation research within economics and management (e.g., Acar et al., 2019; Anderson et al., 2014; Azoulay et al., 2011; Charness and Grieco, 2019, 2023; Ederer and Manso, 2013; Gross, 2020), nuanced investigations into the antecedents of creative output represent a particularly important line of inquiry in psychology and organizational behavior (Hennessey and Amabile, 2010). Likewise, complementary perspectives in sociology have become increasingly rich in recent years (Godart et al., 2020). Indeed, scholars examining micro-level processes of creativity at the individual and group level have detailed how individual differences (e.g., Zabelina et al., 2016), motivations (e.g., Hennessey and Amabile, 1998), and team interactions (e.g., Paulus and Yang, 2000) shape production of creative ideas (see also Amabile and Pillemer, 2012; George, 2007; Harvey and Rietzschel, 2022).

Our work is guided by an effort to better understand the influence of proof-of-concept demonstration of a new technology on subsequent innovative activity that occurs during the pre-commercialization era of the industry lifecycle. We conceptualize proof-of-concept demonstration as the public-facing display of a functioning new technology such that it informs others about the feasibility of this technology. This definition emphasizes three points: (1) that a functioning new technology is demonstrated, (2) it is observed by external audiences, and (3) its success is widely disseminated. As such, proof-of-concept demonstration can serve as a type of "trigger event" that precedes industry inception during its incubation stage (Agarwal et al., 2017). Holistically, however, a lack of scholarly attention to incubation stage activity leaves us with open questions about the early trajectory of new technologies.

The early era of an industry's emergence around a new technology consists of a plethora of creative ideas and approaches that ultimately contribute to technological development but precede pragmatic applications of that technology for commercial purposes (see also Moeen and Agarwal, 2017; Moeen et al., 2020). Placing our construct within this context, proof-of-concept demonstration is more than the establishment of an abstract technological idea or the granting of a corresponding patent. It is a galvanizing event that is characterized by the public demonstration of a functioning new technology that is observed and can be verified by external audiences who propagate news of its success. Thus, it signals the general feasibility of a new technology to others, even if eventual practical applications of the technology still require additional progress. Precisely because commercialization opportunities have yet to materialize for the new technology, innovators are still relatively less constrained by market incentives during this early phase of industry evolution. Accordingly, proof-of-concept demonstration should be understood as being a precursor to the development of commercial prototypes that seek to establish commercial viability and the transition to a technology's implementation (see also Audretsch et al., 2012; Bakker et al., 2012; Lu et al., 2019). Potential innovators working during this "era of ferment," thus, focus on generating creative solutions to technological problems independent of specific market needs (Tushman and Anderson, 1986, p. 440; see also Hennessey and Amabile, 1998).

Scholars working in various areas have underscored the importance of trigger events that direct market actor attention and energies towards new developments (e.g., Cattani et al., 2018; Eggers and Kaplan, 2009; Hoffman and Ocasio, 2001; Kaplan and Tripsas, 2008; Tushman and Anderson, 1986). A stream of work about generating solutions to problems suggests that by providing individuals with an initial example there is a corresponding increase in creative ideas generated (e.g., Nijstad et al., 2002; Siangliulue et al., 2015). Extending this notion to proof-of-concept in nascent technologies, where the feasibility of a novel idea is made salient to others through its demonstration, one should expect that there is an increased proclivity to innovate in that technological domain. That is, being exposed to a functioning invention can spur the creative impulses of others to contribute to its subsequent development (e.g., Sohn et al., 2024a). Thus, we posit that there exists a positive relationship between proof-of-concept demonstration and subsequent innovation. At the macro-level, this should occur at both the intensive and extensive margins. With respect to the intensive margin, for those already working in a focal technological domain, being exposed to an example via proof-of-concept demonstration is likely to intensify their innovative output because it stimulates problem-solving on related issues by showing them what has been successful. At the extensive margin, new inventors are more likely to innovate in a focal technological space because exposure to proof-of-concept demonstration enhances their awareness of a new technology's potential usefulness, along with the current state of technological problems and possible solutions.[3]

The idea that proof-of-concept demonstration can impact subsequent innovation further suggests that proximity matters to the extent that geography moderates the likelihood or intensity of potential innovators' exposure to a functioning new technology. Scholarship has long suggested that innovative activity is likely to cluster in certain areas due to knowledge spillovers (e.g., Audretsch and Feldman, 1996; Jaffe et al., 1993; Marshall, 1890), and the co-location of innovators may be one

[3] Considerations of immediate commercialization opportunities notwithstanding, there is also a pressing question about the conditions under which inventors would be willing to engage in proof-of-concept demonstration. In cases where intellectual property (IP) regimes are weak, it is likely that inventors would be less willing to disclose their progress via proof-of-concept demonstration because others may appropriate their advances for their own gains. Strong IP protections, on the other hand, may encourage innovators to disclosure their early breakthroughs through proof-of-concept demonstration because subsequent technological advances made by others could hasten the time it takes to develop a commercializable technology, and proof-of-concept demonstration could be strategic insofar as it encourages others to build off of their design. The overall effect on technological progress and industry development, however, is not straightforward as it should also be understood to be subject to other factors related to the strength of IP regimes (see also Boldrin and Levine, 2008; Jaffe and Lerner, 2004); indeed, strong IP protections can also hinder future commercialization and industry growth independent of subsequent technological progress if the holders of the IP use it to prevent others from commercializing the technology. Note that we address these issues further with respect to our context of early aviation in Discussion Section 5.2.

factor that facilitates the transfer of the tacit knowledge that is crucial for further technological advances (e.g., Petralia et al., 2023). While transportation infrastructure (e.g., Agrawal et al., 2017; Catalini et al., 2020) or information technologies (e.g., Agrawal and Goldfarb, 2008; Ding et al., 2010; Forman and Zeebroeck, 2012) may lessen the impact of distance by enhancing the flow of knowledge, this body of literature would suggest that being geographically proximate to the site of proof-of-concept demonstration has an influence on subsequent innovation outcomes. Thus, we posit that those areas that are more closely located to a proof-of-concept demonstration site exhibit a relatively greater increase in subsequent innovative output.

Returning to the micro-level literature on antecedents of creativity, another key finding from this body of research helps inform us as to the plausible consequences of proof-of-concept demonstration on subsequent innovation. Prior work has shown that after exposed to an example or template, individuals' newly generated solutions may more closely reflect the example provided (e.g., Marsh et al., 1996; Smith et al., 1993; Ward, 1994). With respect to technological progress, this suggests that following proof-of-concept demonstration there may be a relative increase in innovators' focus. So, on one hand, even as more innovations occur after proof-of-concept demonstration, the distribution of what types of innovations take place may also change, and it may lead to a narrowing of the range of alternative designs being produced. This would suggest that work becomes concentrated in some areas after others become exposed to a functioning invention. On the other hand, however, prior research has emphasized that exposure to new ideas can have a positive effect on creativity in related and adjacent areas (e.g., Agogué et al., 2014; Chan et al., 2011; Nijstad et al., 2002), especially if concepts or skills are transferable between them. This then suggests that proof-of-concept demonstration in one domain may also have a positive spillover effect on related domains by spurring innovators to begin working in the broader technological category and consider alternative approaches that furthers development in various areas.

In bringing together micro-level processes of creativity with technological progress and innovation, we can extrapolate additional macro-level considerations related to industry formation and development (see also Akcigit and Nicholas, 2019). In particular, an increase in output and focus of innovators may provide an impetus for actors to more formally arrange economic activity around a focal technology. This is because corresponding advances in a technology likely makes subsequent innovative activity more costly and necessitates greater resources coupled with complimentary capabilities (Bryan, 2023). Research underscores that diverse groups create superior solutions when problems are complex (e.g., Hong and Page, 2004), and a stream of work has highlighted how the burden of knowledge encourages team production (e.g., Jones, 2009). However, we should be cautious about extrapolating potential commercialization era consequences to the incubation phase immediately following proof-of-concept demonstration because a shift in locus of innovation to corporate actors likely only manifests after market opportunities for a new technology become apparent to a focal firm or those they perceive as their competitors (Cattani et al., 2018; Sands et al., 2021). When such market opportunities begin to appear, firms may be relatively better positioned to transpose complex ideas and apply their diverse capabilities to a new technological domain for commercialization purposes (Acemoglu et al., 2022; Cattani, 2005; Klepper and Simons, 2000). This, therefore, indicates that even while both individual and corporate inventors may increase their innovation output following proof-of-concept demonstration, the locus of innovative activity and technological development may remain primarily in the hands of individual inventors and only begin to shift to corporate entities after commercialization opportunities begin to materialize.

Prior research has emphasized that technological progress is aided by the local exchange of ideas (e.g., Jaffe et al., 1993; Rosenberg, 1970; Von Hippel, 1994). A denser information environment and the relative advantage of co-located value chain actors in an area may facilitate innovation (e.g., Helfat and Campo-Rembado, 2016; Hu et al., 2019; Sohn et al., 2024a), and these factors can result in innovation clustering in certain geographic areas (e.g., Audretsch and Feldman, 1996; Delgado, 2020; Delgado et al., 2014). Moreover, researchers investigating the social structure of creativity and innovation have emphasized that social ties play an important role in developing solutions to problems (e.g., Hauser et al., 2007; Perry-Smith, 2006; Rost, 2011). We, therefore, should expect that proof-of-concept demonstration results in a geographic shift in innovative output that leads to increased concentration of innovative activity in areas with greater amounts of pre-existing human capital, resources, or key capabilities. While it may be contingent on particular characteristics of a new technology, the important role played by individual inventors during the industry's incubation stage, nevertheless, indicates a relative importance of concentrated human capital that is better suited to mobilize pre-existing knowledge and skill towards addressing a new technology (e.g., Cohen and Levinthal, 1990). Accordingly, a second-order effect of proof-of-concept demonstration is that it can intensify innovation within geographic areas that were already especially innovative, even if prior innovations from these areas were not in the focal domain of the newly demonstrated technology.

As an integral part of our approach to developing a deeper understanding of these issues, we use this theoretical foundation as the basis for our empirical investigation of aviation innovation during the late 1800s and early 1900s. This allows us to iterate between theory and empirical evidence to better understand a phenomenon that is not well explained in current theory (e.g., King et al., 2021; Sætre and Van de Ven, 2021), which is an especially fruitful avenue given our efforts to link together micro-level processes of creativity with macro-level processes of technological development and industry formation. Moreover, the "history-to-theory" approach that we apply with this historical case study provides important contextualization that enables us to balance deepening our understanding of the setting with distilling generalizable insights for scholars working in other areas (Argyres et al., 2020; see also Agarwal et al., 2017; Baldwin et al., 2006; Holbrook et al., 2000; Silverman and Ingram, 2017). Accordingly, our analyses of the effect of proof-of-concept demonstration on aviation innovation outcomes that appear in the subsequent sections follow the logic laid out in this theoretical foundation, and we further extend our theorizing based on evidence provided by our empirical examination.

3. Empirical investigation

Our empirical investigation is supported by accesses to extensive primary source material related to early aviation and the development of flight. Notably, the "Wilbur and Orville Wright Papers" and "Octave Chanute Papers" collections held by The United States Library of Congress provide access to thousands of individual items that help inform our study. In addition to files on aircraft design, records of progress, and personal diaries, both of these collections also contain letters of correspondence between these individuals and other key figures working in aviation at the time (e.g., Wright, 1900). Another key source of primary documentation that we have constructed for this study is the corpus of granted USPTO aviation patents granted between 1894 and 1913; these total more than 2000 patent documents and provide very nuanced information about aviation innovation that have been central to our study (we expand more on these data in Section 3.3 when detailing our approach to quantitative analyses). We make specific reference to the contents of individual patents to illustrate key points throughout the manuscript. This work is also supplemented by a wide range of other contemporaneous second-hand accounts of aviation related activities that help us to temporally situate our investigation within the context of flight in this era. These include a wide range of media coverage of key events (e.g., New York Times, 1908a, 1908b) and commentary on broader developments within the industry (e.g., New York Times, 1909). Likewise, we build on a detailed body of much earlier scholarship that collected key relevant information about issues related to those that we study in this article—most notably, the works of Gibbs-Smith, who began extensively publishing on the topic as early as 1950. These volumes provide ample information about key developments, and this has greatly aided us in our study and allowed us to corroborate our research with information that scholars working much more closely in time to these events were able to obtain. We note, too, that more recent scholarship has also build directly from some of the above sources (e.g., Barnett, 2015; Bittlingmayer, 1988), and our efforts here are guided by from crucial insights made by these scholars, as well.

3.1. The 'invention' of the airplane

The dream of human flight has been long and storied (see Gibbs-Smith, 1960). However, it was not until December 17, 1903, on a beach in North Carolina, did mankind achieve powered flight. In private experiments, Wilbur and Orville Wright, Ohio-based bicycle-manufacturers-turned-airplane-inventors, flew three flights totaling less than three minutes and 500 feet of distance that day. After refining their airplane and continuing to fly in private near their Dayton workshop, the Wrights first offered public demonstrations of their flying starting in 1908. This proof-of-concept demonstration of airplane-powered flight enthralled audiences in attendance, and the details of their demonstration were further amplified by media coverage around the world. The Wrights received widespread acclaim for their accomplishments, as their transformation of powered flight from a dream to reality marked a watershed moment in technological progress.

The Wright brothers' key contribution to the invention of the airplane, which allowed them to provide proof-of-concept demonstration, was derived from their recognition of the importance of wing stability and flight control. Indeed, their core airplane patent underpinning their ability to fly, which was granted in 1906 (US821393A),[4] referenced the need to "provide means for maintaining or restoring the equilibrium or lateral balance of the apparatus." Their due credit for their achievement notwithstanding, inventors working all over the world were also making progress on powered flight, and the Wright brothers built on a collective body of knowledge that spanned many years. Their iterative hands-on approach of learning-by-doing, over many years of trials and against a backdrop of their mechanical expertise and support (McCullough, 2015; Renstrom, 2003), allowed them to be the first to accomplish this historic feat. Following the Wrights, other inventors would also achieve powered flight with their own airplanes and help to expand the collective recognition that technological progress here had finally taken off.

The link between the early idea of powered flight and the modern global networks of air travel, in which billions of passengers fly annually, is long and complex. Nevertheless, the shock of proof-of-concept demonstration is a key event in this path (Gibbs-Smith, 1960). Accordingly, the following sections provide a detailed examination of this critical juncture as a trigger event in the creative process of aircraft development. Following Moeen et al. (2020), we concentrate on describing actors and their prior knowledge, new knowledge generation, knowledge-aggregation mechanisms, and the commercial milestones that underpinned innovation and technological progress during the aviation industry's pre-commercialization incubation stage.

3.2. Creativity, proof-of-concept, and aviation innovation in the United States

For centuries, the prospect of flight had been mostly limited to mythology,[5] the unrealized creative constructs of polymaths (Güss et al., 2021), or attempts at glider-type apparatuses (White, 1961). Industrial and scientific advances in the 19th century, however, made the possibility of powered flight a much more tangible prospect for inventors (Gibbs-Smith, 1960, p. 23), and innovators around the world devoted considerable attention and effort to the problem of flight. By the time the first successful manned glider had even taken flight in the mid-1800s (Gibbs-Smith, 1962), lighter-than-air hot air balloons had been taking people in the skies for decades (Gibbs-Smith, 1957). Hot air balloons had even been employed in various military engagements in Europe and the United States, including the American Civil War when a Balloon Corps was established (Haydon, 2000). The practical advantage of fixed-wing aircraft traveling vast distances at high-speeds, however, kept scores of inventors in the United States focused on creating such a device. Notably, these included renowned inventors Samuel Langley and Octave Chanute who had both corresponded with the Wrights in the years leading up to their first successful powered flight (Wright, 1899, 1900; see also McCullough, 2015).

Despite the fact that (or, perhaps, because of it) there seemed to remain a persistent interest in achieving powered flight, but with a lack of results, aspiring innovators working in this space could be easily dismissed or even met with ridicule. For example, newspapers such as The San Francisco Chronicle were describing aviation innovators as "flying-machine cranks" as a pejorative for those working on obviously unaccomplishable and foolhardy tasks, and they disparaged those working in the field, saying that: "Aerial navigation has always had an irresistible fascination for the fraternity of cranks" (San Francisco Chronicle, 1890, p. 6). In an article published in 1896, The Washington Post, writing skeptically about aviation progress declared that: "The confidence entertained by the inventors in the practicability of their flying machines is utter and absolute" (Washington Post, 1896, p. 9). The New York Times (1903, p. 6), in an article titled "Flying Machines Which Do Not Fly," commenting later on the failure of Smithsonian Institution Secretary Samuel Langley's Aerodrome remarked: "The mistake of the scientist would appear to be in his assumption that he can do with much less suitable material by a single act of creative genius what nature accomplishes with such immeasurable deliberation." These criticisms aside, the idea of flight was captivating to a great many people, and some of the country's most serious inventors saw it as being on the horizon.

The Wright brother's September 1908 public proof-of-concept demonstrations at Fort Myer, Virginia, signaled that the longstanding dream of powered flight was, in fact, in hand (see New York Times,

[4] Prior research has investigated the extent to which the development of the aviation industry in the United States was affected by early patent disputes or the 1917 patent pool; while beyond the scope of this article, these works offer key insight into the later commercialization phase of the industry's evolution (e.g., Bittlingmayer, 1988; Johnson, 2004; Katznelson and Howells, 2015). We engage these issues in more detail in Discussion Section 5.2.

[5] Creative ideas about how to build a flying device has been a staple of innovators' imaginations for thousands of years. Indeed, the very idea of humans flying is depicted in Greek mythology with the story of Daedalus and his son Icarus. A translation of the name Daedalus, the mythical Greek inventor of flight, has been suggested as meaning "skillfully wrought" (Britannica, 2023)—seemingly prescient of the Wrights' particular efforts in building their airplane.

1908a).[6] Widely recognized via media coverage of the Wrights' public demonstrations, this marked the beginning of the transition to making aircraft more effective and eventually practical (Gibbs-Smith, 1960). Indeed, their accomplishments constitute a canonical proof-of-concept demonstration event in the history of invention, and it remains well celebrated today. While the Wrights' work is often presented as the invention of the airplane, we contend that it is more accurate to say that that their invention provided a demonstration of proof-of-concept of the airplane. This nuance articulates two points. The first is that the invention of the airplane was a process that began well before the first flight occurred, and many important ideas provided by many innovators over many years contributed to the successful first flight. The second is that the invention of a *pragmatic* airplane was a process that did not end with the technology's proof-of-concept demonstration, and many important ideas provided by many innovators over many more years would contribute to the success of the airplane as a practical device that would only much later have significant commercial application.

It is also important to stress that the core contribution of the Wright brothers' work that led to the first powered flight was creative and collaborative in nature, rather than as some sort of isolated scientific discovery about flight's fundamental properties (Bryan, 2023). Indeed, the Wrights drew from others working in this space—through both published documentation and their personal interactions. Like their predecessors' designs, their first plane was made of wood and fabric, and it used an externally-sourced 12-horsepower aluminum engine that was customized by the Wrights' mechanic, Charles Taylor (see also Wolko, 1987). For the next two decades, airplanes would predominantly still be made out of wood instead of metal, but the design of planes continued to evolve. While there was certainly no shortage of technological advances that contributed to the development of the airplane during this time period, it was ultimately the creative combination of novel ideas, learning-by-seeing, and learning-by-doing that best holistically characterizes aviation innovation in the early 20th century.

In the decade after the first powered flight demonstrations, there was rapid technological progress and advances in airplane capabilities (see Appendix Table A1 and Appendix Fig. A1). Exhibitions provided displays of airplanes for aviation enthusiasts, media, and the general public. Pilots continued to accomplish new feats and showcased increases in aircraft performance, and various prizes and awards were sponsored to encourage pilots and inventors to push the limits of flight.[7] Early aircraft were still dangerous and often unreliable, and 1908 marked the first death resulting from an airplane crash when airplane inventor and U.S. Army Lieutenant Thomas Selfridge was killed during a crash in a Wright Flyer that was being piloted by Orville Wright (New York Times, 1908b, p. 2; see also Maksel, 2021).

Airplane manufacturers began being established throughout the country before the end of the first decade of the 1900s, and the Wright brothers incorporated their Wright Company in 1909 (see also patent US987662A: "Flying-machine"). Glen Curtiss, also in 1909, transitioned from engine to aircraft design and established the Curtiss Aeroplane Company (originally named the Herring-Curtiss Company, it later became the Curtiss Aeroplane and Motor Company—see also patent US1204380A: "Flying-machine"). While still limited in scope compared to Europe (Bryan, 2023), within the next few years, more than two dozen new companies in the United States focused on the development and production of airplanes or aviation equipment (see Appendix Table A2).[8] Nevertheless, companies appeared to have been less involved with aircraft innovation compared to individuals in these early years of flight, which further highlights a lack of commercial applicability for this newly demonstrated technology. World War I, the start of which marks the end of our work's period of study, saw enhanced government support of aviation technology because the employment of numerous different types of airplanes, first for aerial surveillance and later for use in air-to-air combat, proved to be increasingly important on the battlefield (see also Maurer, 1978).[9] Significant civil applications of airplanes appeared in the United States towards the end of World War I when Congress authorized the Post Office Department to use Army pilots and surplus planes to establish airmail delivery across the country (Sohn et al., 2024a).

Our article next turns to quantitatively examine the question: How did proof-of-concept demonstration of the airplane shape the intensity of aviation innovative activity in the United States? As our theorizing and historical investigation make explicit, this is inescapably an intertwined micro- and macro-level question that illustrates the complexity underpinning creative processes and innovation outcomes. Comprehensively investigating the effect of proof-of-concept demonstration on innovation during our period of study, therefore, requires that we collect and analyze historical records to understand who was innovating and what types of innovations were being produced. It also requires that we zoom out and provide a macro-level view of the distributions of inventions in order to understand if and how different regions were set on different trajectories. In doing so, this multi-level approach we take with our case study provides a broad apparatus that can deepen our understanding of the effect of the proof-of-concept demonstration of the airplane on aviation innovation during the late 19th and early 20th centuries.

3.3. Quantitative investigation

In this section we detail the empirical approach and data construction efforts that underpin our quantitative investigation. We focus on the era around proof-of-concept demonstration of the first powered flight, and thus, we sought to collect information about all aviation inventions that occurred before and shortly after this event so we can better understand the trajectory of innovation during this incubation phase. Our data come

[6] These first public proof-of-concept demonstrations occurred nearly five years after their first privately conducted flights in North Carolina.

[7] Research about awards and prizes suggests that these contests could have had a notable impact on technological progress and the success of firms (Frey and Gallus, 2017; Gallus and Frey, 2016; Galasso et al., 2018). Relatedly, Rao (1994) highlighted how early automobile manufacturers' success in certification contests enhanced their survival (see also Goldfarb et al., 2018). Bryan (2023), however, emphasizes that a focus on prizes may have had a limited effect in supporting the development of an aviation industry in the United States due to a lack of complementary capabilities needed for technological progress.

[8] The response to proof-of-concept demonstration was global. In part, this was due to the Wrights' international circulation and widespread media acclaim. The New York Times (1909, p. 4), following an extended and well-attended French flying exhibition held by the Wrights, noted: "The builders of airplanes in Paris and its neighborhoods could be counted on the fingers of one hand six months ago. To-day there are fifteen factories in full operation. Scores of inventors are constructing their own machines. There is an aerodrome where pupils are taught to fly. Three new papers devoted to aviation have been founded within the past six months. There are three societies in France for the encouragement of aviation, and over $300,000 in prizes will be open to competition in the course of the year. These few facts show very clearly the extraordinary rate at which the new industry is growing in France."

[9] Our study focuses on the early phases of technological progress that occur during the incubation stage of industry evolution. The aviation industry developed significantly during the interwar period, which was a dynamic era of its commercialization phase. As noted earlier, the first dominant design was established in the mid-1930s with the Douglas Aircraft Company's (founded in 1921) development of the DC-3 (Tushman and Murmann, 1998). The DC-3 was a 21-seat two-engine airplane that could transport passengers and cargo across the country in 16 hours with just a few stops (Howe, 1946), and it was the first airplane to make passenger traffic and transport economically feasible without airmail subsidies (Sohn et al., 2024). Notably, with respect to our article's context, the company's founder, Donald Wills Douglas, was in the audience during Orville Wright's 1908 flying demonstration at Fort Myer (Johnson, 1984).

Table 1
Descriptive statistics.

(a) Nation-year level descriptive statistics, 1894–1913.

Variable	Mean	Std. Dev.	Min.	Max.
Aviation patents	99.9	124.898	9	411
Individual aviation patents	87.8	118.223	0	380
Corporate aviation patents	6.05	7.997	0	28

(b) County-year level descriptive statistics, 1894–1913.

Variable	Mean	Std. Dev.	Min.	Max.
Year	1903.5	5.766	1894	1913
Aviation patents	0.036	0.585	0	61
Individual aviation patents	0.033	0.536	0	54
Corporate aviation patents	0.003	0.078	0	7
Non-aviation patents	10.456	86.598	0	4238
Fixed-wing airplane patents	0.015	0.281	0	31
Alternative flying devices patents	0.010	0.193	0	14
Population (interpolated)	28,602.57	81,819.63	1.6	2,762,522
Manufacturing establishments (1900)	197.472	878.672	0	27,168
Pre-1908 sum of non-aviation patents	237.992	1865.788	0	71,495
2872 counties; observations = 57,440				

from a variety of sources. We started with historical patent information available from the U.S. Patent and Trademark Office (USPTO), and then used HistPat[10] data to obtain inventor location information. We used the Google patent database to supplement the USPTO data with inventor name, assignee name, grant date, patent class. We then incorporated county-level historical measures from the U.S. Decennial Census[11] to provide locality-specific characteristic information. This resulted in a dataset of patents that we analyze at the county-year level.[12]

In linking these sources together, we constructed a dataset that contains information about all USPTO aviation patents granted between 1894 and 1913. We chose this date range because 1894 marks the year after Otto Lillenthal began to serially produce the first manned gliders and the year of Octave Chanute's (1894) aviation research compilation book, "Progress in Flying Machines," was published—both served as key sources of inspiration for the Wright brothers (McCullough, 2015, pp. 28–29, 39–40; see also Gibbs-Smith, 1960, pp. 28–35; see also Wright, 1900). Thus, our sample begins a decade before the Wright brothers' first flight, and we uniquely document innovative activity that preceded the invention of the airplane, which has been notably absent from studies of the aviation industry that focus on the commercialization era. The final year of our dataset is 1913, which is the year prior to the start of World War I. As noted earlier, aircraft began receiving substantial government investment during the war and were employed for both non-combat and combat roles, marking the practical application of the airplane.

We first identified a patent as an aviation innovation if the patent was classified as aircraft and aviation-related by the patent office (i.e., assigned to International and Cooperative Patent Class (IPC/CPC) B64, B21D 53/92, or U.S. Patent Class (USPC) 244) or if the patent contained aviation-related words and variations that were common in the era, such as "aeroplane" or "flying machine," appearing in the title or main text. We also manually inspected the main text to exclude false positives like windmills, rotary churns, and marine propellers.[13] Since our focus is on the evolution of innovative activity in the U.S., we only retained patents with at least one U.S.-based inventor. The resulting dataset contains more than 2000 aviation patents granted between 1894 and 1913.

Table 1 presents key summary statistics of our patent data and county-level variables such as population and the number of manufacturing establishments. As shown in Fig. 1, we observe in our raw data that the aviation sector experienced a much greater increase in innovative output during our window of observation compared to other means of transportation such as ships, railcars, and carriages. The moderate uptick between 1904 and 1907 reflects the innovative activity pursued by the earliest aviation pioneers, including the Wright Brothers, prior to their public demonstration. There was substantial growth in innovative activity between 1908 and 1911, and even with the relative decline during 1912 and 1913, the annual number of patents filed in 1913 was more than twice the number filed in 1907. This pattern in these raw data seems to be consistent with our historical narrative about the role of the 1908 proof-of-concept demonstration.

3.4. Method

The baseline statistical approach that we take with our main analyses is conditional fixed effects quasi-maximum likelihood (QML) Poisson regression to estimate the effect of proof-of-concept demonstration on our innovation measure at the county-year level. Our main dependent variable is the count of *Aviation Patents* that were filed in a given county for each year. For some analyses, we use patent assignee information to separately examine individual and corporate patents or to distinguish different types of aviation patents, such as fixed-wing airplanes and alternative flying devices.[14] Our primary independent variable of interest is *Post Proof-of-Concept*. This binary variable captures the effect of airplane proof-of-concept demonstration. It is equal to one starting in 1908, which reflects when the general public became exposed to the powered flight demonstration. Accordingly, the following estimating equations relate innovative output of county i in year t to proof-of-concept demonstration:

$$E[\text{Aviation Patents}_{it}] = exp[\alpha \text{ Post Proof-of-Concept}_{it} + \gamma \text{Population}_{it} + \delta_i],$$

[10] See Petralia et al. (2016) for additional general data information.

[11] See Haines (2010) for additional general data information.

[12] We make these data available for other researchers at https://github.com/ehsohn/airmail_data.

[13] For example, a patent related to rotary churns used to agitate milk (e.g., US802972A) was assigned to CPC B64C11 ("Propellers, e.g. of ducted type; Features common to propellers and rotors for rotorcraft") because they involve the use of rotating blades; however, since these are not relevant to aerial propellers, such cases were excluded.

[14] We also use patent content information, notably CPC subgroups, to distinguish between the types of innovations that are being worked on within each particular patent, and we provide additional information about this approach when discussing the relevant analyses in the subsequent section.

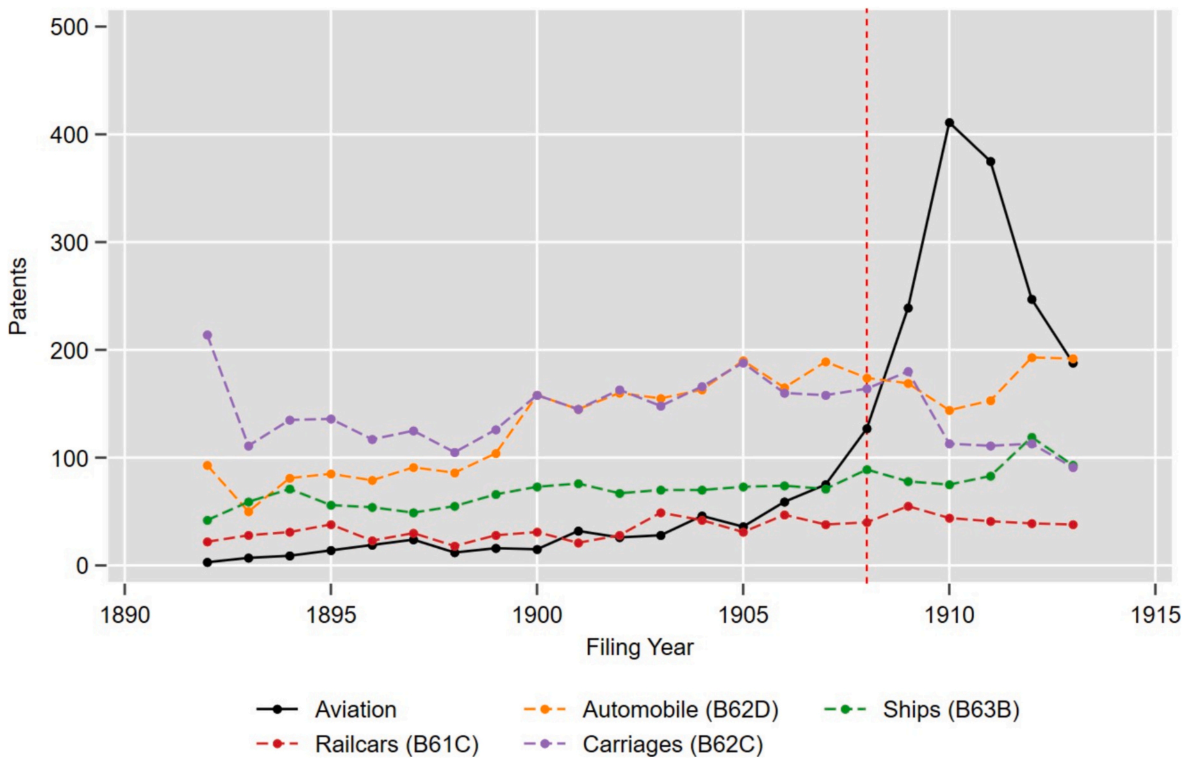


Fig. 1. Patenting in aviation vs. other transportation technologies.

where $Population_{it}$ is the log of county i's population in year t. δ_i are county fixed effects that control for time-invariant characteristics that may affect a county's level of innovative output.[15]

Following our main analyses, we then interact *Post Proof-of-Concept* with variables that capture other county-level features. These include geographic proximity to the proof-of-concept demonstration and levels of non-aviation patenting, manufacturing output, and population to explore the variation in treatment intensity across different counties. For these analyses, our estimating equation is:

$$E[\text{Aviation Patents}_{it}] = exp[\alpha \text{ Post Proof-of-Concept}_{it} + \beta \text{ Post Proof-of-Concept}_{it} \times X_{it} + \gamma \text{Population}_{it} + \delta_i],$$

where X_{it} is a vector of county-level variables that represents a county's proximity to the proof-of-concept demonstration, a county's capacity in non-aviation patenting, manufacturing output, and population. β is a vector of coefficients that captures their interactions with *Post Proof-of-Concept.*

4. Results

4.1. The trajectory of innovation: inventor activity and creative focus

Our first set of analyses considers the relationship between proof-of-concept demonstration and subsequent innovation. The *Post Proof-of-Concept* coefficients from Table 2 suggest a positive effect on aviation patenting across all model specifications. We interpret the main result from Model 2, for example, as indicating that aviation innovation increased by 376 % following proof-of-concept demonstration.[16] While Models 1 and 2 include all patents regardless of their assignee, Models 3–6 allow us to consider, separately, individual and corporate inventors, and we also observe a positive effect of proof-of-concept demonstration for each (e.g., Model 4: $\beta = 1.602$; *95 % CI* = [1.369, 1.836]; Model 6: $\beta = 1.082$; *95 % CI* = [0.244, 1.920]). Nevertheless, the magnitude of the increase in innovative output appears marginally greater for individual inventors compared to corporates,[17] and we observe more than ten-times as many individual inventor patents being produced throughout our period of study, as shown in Fig. 2. As we noted earlier, a lack of commercialization opportunities during this era likely kept the locus of innovation in the hands of individual inventors rather than firms.[18] Indeed, the aviation industry does not appear to have this gap closing until its commercialization phase in the late 1920s and early 1930s (see Appendix Fig. A2), which underscores the important role that individual inventors played in shaping the trajectory of aviation technology during the incubation stage that we study here. This is consistent with the notion that creative impulses spurred by proof-of-concept demonstration were driven by a general desire to advance the focal technology, as opposed to addressing corporate objectives related to commercialization, which is reinforced by our review of historical material (see again Section 3.2).

We next use the physical site of the proof-of-concept demonstration in order to examine the extent to which these observed effects are

[15] For the sake of robustness, we provide results from various specifications of this general estimating equation in the following section, to include with/without controls and random/fixed effects models.

[16] $(e^{1.562}–1) = 3.76$.

[17] The difference of 0.52 between Model 4 and Model 6 coefficients has a *95 % CI* = [−0.280, 1.321], which we calculated using bootstrapping.

[18] As referenced in the discussion of our archival work, we still see a notable set of de novo firms begin to patent during this period; see Appendix Table A2. Accordingly, we find patenting from both de novo and de alio corporate inventors following proof-of-concept demonstration. For example, the de novo Connecticut Aircraft Company files for "Flying-machine" US1118881A in 1909 and the de alio Pennsylvania Rubber Company files for "Aeroplane-wing" US1008630A in 1910.

Table 2
Post proof-of-concept changes in aviation innovation in the United States, 1894–1913.

DV = Aviation patents	(1)	(2)	(3)	(4)	(5)	(6)
	All		Individual		Corporate	
Post Proof-of-concept	1.986*** (0.052)	1.562*** (0.119)	2.011*** (0.054)	1.602*** (0.119)	1.694*** (0.237)	1.082**(0.428)
Population(logged)	1.453*** (0.036)	3.323*** (0.680)	1.448*** (0.034)	3.219*** (0.683)	1.515*** (0.076)	4.698*** (1.742)
County FE	No	Yes	No	Yes	No	Yes
Observations	57,440	9240	57,440	8940	57,440	1420
Counties	2872	462	2872	447	2872	71
Log likelihood	−4417.34	−2353.05	−4178.85	−2226.78	−618.97	−279.66

Notes: Poisson regression coefficients with robust standard errors clustered at the county level in parentheses. *P* value in square brackets.
* $p < 0.1$.
** $p < 0.05$.
*** $p < 0.01$.

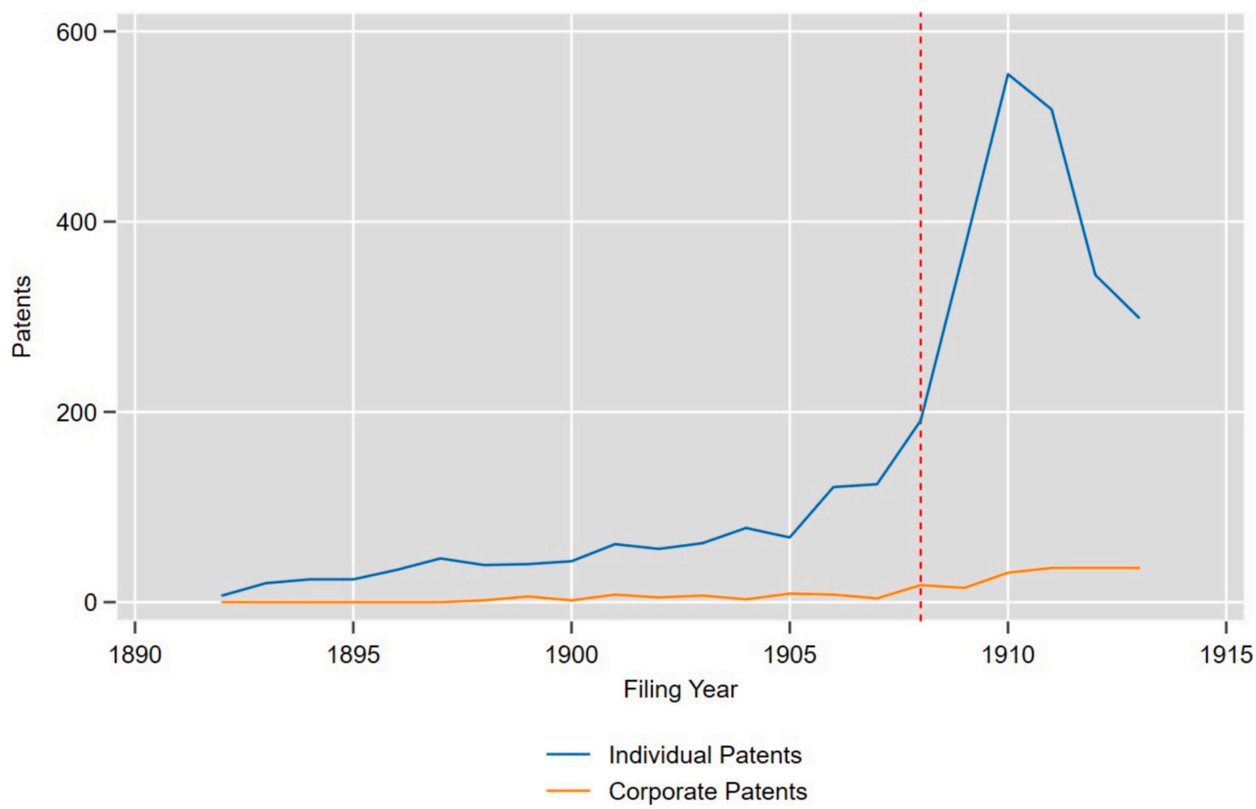


Fig. 2. Individual and corporate inventor aviation patent output in the United States, 1894–1913.

geographically bounded. Provided that there is a stickiness to knowledge spillovers, being at or close to the proof-of-concept demonstration site would be likely to have a stronger impact on subsequent innovation outcomes given that those in close geographic proximity would be more likely to be exposed to the new technology. In this setting, the airplane proof-of-concept demonstrations of 1908 all occurred at Fort Myer in Arlington County, Virginia.[19] Accordingly, we introduce a series of localization variables in the subsequent analyses to capture the effect of geographic proximity. These variables distinguish between the counties that are at or adjacent to the demonstration site[20] (*At/Adjacent to Site* in Models 1 and 2) and counties at a various distances from the demonstration site (*0–50 Miles Away*, *50–100 Miles Away*, *100–200 Miles Away* in Models 3 and 4). We interact these variables with *Post Proof-of-Concept*, to estimate the localization effect of proof-of-concept demonstration on subsequent innovation.

Table 3 continues to display a positive effect for *Post Proof-of-Concept*, and the interaction effects from the various analyses indicate that geographic proximity to the proof-of-concept demonstration site had a distinct positive influence on subsequent innovation. For example, the coefficient on *Post Proof-of-Concept* × *0–50 Miles Away* in Model 4 is 0.300 (*95 % CI* = [0.115, 0.486]), signifying that the increase of innovative output among those counties within 50 miles of the demonstration site was 35 % greater than in counties more than 200 miles away.[21]

[19] Orville Wright's most notable demonstration flights at Fort Myer occurred on 9, 10, 11, and 12 September 1908 and totaled >200 miles over 5 ½ hours of flight time (see Gibbs-Smith, 1960).

[20] These counties include Arlington VA, Alexandria VA, Fairfax VA, and Washington DC.

[21] $(e^{0.3}–1) = 0.349$.

Table 3
Post proof-of-concept changes in aviation innovation by distance from the demonstration site.

DV = Aviation patents	(1)	(2)	(3)	(4)
	At/adjacent		By distances	
Post Proof-of-concept	1.977^{***} (0.054)	1.546^{***} (0.118)	1.998^{***} (0.057)	1.563^{***} (0.122)
At/adjacent to site	1.824^{***} (0.088)			
Post Proof-of-concept × at/adjacent	0.264^{***} (0.071)	0.371^{***} (0.080)		
0–50 miles away			1.713^{***} (0.157)	
50–100 miles away			0.322 (0.395)	
100–200 miles away			−0.218 (0.265)	
Post Proof-of-concept × 0–50 miles			0.206^{**} (0.087)	0.300^{***} (0.094)
Post Proof-of-concept × 50–100 miles			-0.693^{*} (0.356)	−0.414 (0.292)
Post Proof-of-concept × 100–200 miles			−0.225 (0.184)	−0.057 (0.180)
Population(logged)	1.453^{***} (0.037)	3.327^{***} (0.676)	1.462^{***} (0.036)	3.307^{***} (0.678)
County FE	No	Yes	No	Yes
Observations	57,440	9240	57,440	9240
Counties	2872	462	2872	462
Log likelihood	−4318.38	−2352.09	−4316.70	−2351.80

Notes: poisson regression coefficients with robust standard errors clustered at the county level in parentheses. P value in square brackets.
* $p < 0.1$.
** $p < 0.05$.
*** $p < 0.01$.

It is important to note that in this era, travel was more difficult and costly than it is today, and those living near the demonstration site would have been much more likely to have been exposed to it than innovators who would have had to travel more substantial distances. This evidence, therefore, appears consistent with the notion of stickiness of knowledge due to the importance of tacit information (e.g., Jaffe et al., 1993; Von Hippel, 1994). Moreover, it underscores the potential impact of direct exposure to proof-of-concept demonstration, even as we still do observe a general increase in innovation across a wider geography.

We next exploit heterogeneity between local regions to identify factors that may have led to stronger increases in subsequent aviation innovation. Indeed, not only do we see that the magnitude of aviation patenting increased following proof-of-concept demonstration, but in Fig. 3, we also observe that the concentration of aviation innovation appears to have shifted to new areas of the country. Thus, we seek to address why some areas may have become relatively more engaged in aviation patenting. We introduce three new county characteristic variables for these analyses: *Top Quartile in Non-aviation Patenting*, *Top Quartile in Manufacturing*, and *Top Quartile in Population*.[22] Respectively, these variables capture information about how much non-aviation patenting occurred in an area prior to 1908 (i.e., pre-existing innovative capability in non-aviation technologies), the area's number of manufacturing establishments (i.e., pre-existing commercial and manufacturing experience), and if the area was a population hub (i.e., pre-existing generic human capital). In Table 4, we interact each of these three variables with *Post Proof-of-Concept* to estimate if they had a distinct effect on subsequent innovation.

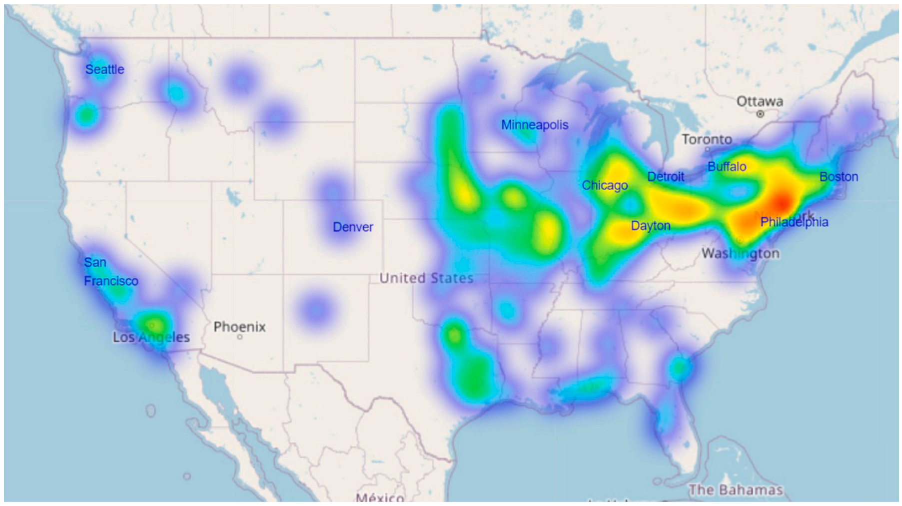
In Table 4, we continue to find a positive effect for *Post Proof-of-Concept*, and the interaction effects from these analyses indicate that local areas' prior patenting activity had a distinct influence on subsequent innovation. The coefficient on *Post Proof-of-Concept* × *Top Quartile in Non-aviation Patenting* in Model 5 is 0.849 (*95 % CI* = [0.208, 1.489]), suggesting that the post proof-of-concept increase of innovative output among the counties in the top quartile of prior patenting was greater than the rest of the counties by 133 %. In contrast, the coefficient on *Post Proof-of-Concept* × *Top Quartile in Population* is negative and significant, implying that while counties with greater population were initially leading in aviation innovation, smaller counties began catching up after 1908.

This illustrates how pre-existing innovative capability may have been deployed to aviation following proof-of-concept demonstration. Our finding here is consistent with the idea that regional-level absorptive capacity can make some areas better suited to address new problems (Cohen and Levinthal, 1990), even as we note that all of these regions still displayed general increases in aviation innovation following proof-of-concept demonstration. High levels of pre-existing innovative experience appear to have allowed these localities to better exploit aviation's emerging technological opportunities provided by proof-of-concept demonstration relatively sooner or relatively more aggressively than others during this incubation phase. As Cohen and Levinthal (1990) note in their theory of absorptive capacity, "prior possession of relevant knowledge and skill is what gives rise to creativity, permitting the sorts of associations and linkages that may have never been considered before" (p. 130). Indeed, our review of archival material provides considerable evidence that innovators working in other technological domains applied their existing expertise to airplanes following proof-of-concept demonstration. For example, we observe that innovators that had been working and patenting in various areas, such as vehicle steering, engine mechanisms, and electromagnetic signaling, applied these capabilities to aviation innovation following proof-of-concept demonstration of the airplane.[23]

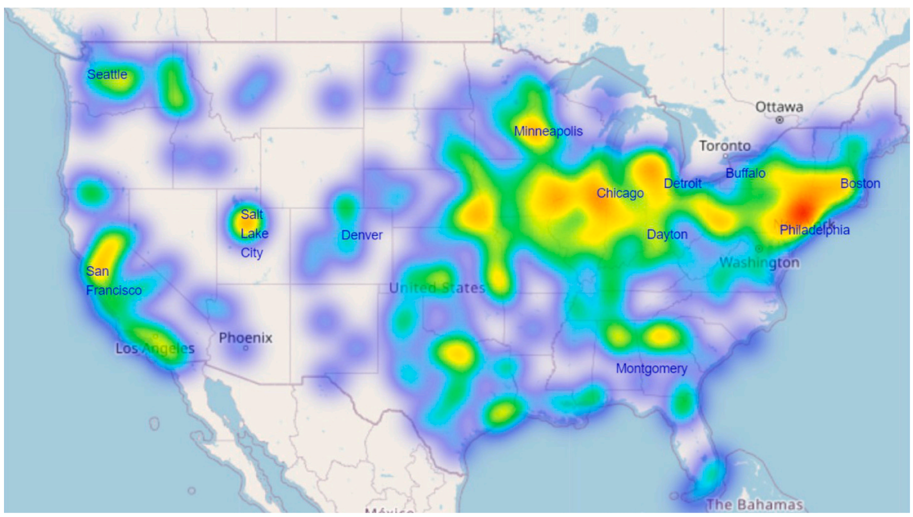
We next dig more deeply into the content of these aviation patents in order to investigate what sort of innovations emerged following proof-of-concept demonstration of the airplane. First, we examine the expansion of idea space within airplane designs by using the number of

[22] To examine how county-level characteristics moderate the impact of proof-of-concept on innovative output, we constructed the respective variables using pre-1908 non-aviation patenting output, 1900 manufacturing establishment counts, and 1910 population counts. We used the relevant U.S. Decennial Census volumes close to 1908 to calculate the manufacturing and population quartiles, noting that the 1910 census did not report manufacturing establishment counts.

[23] As to these specific examples, see, respectively, inventors Walter Marr (US756670A then US1059480A in 1910: "Balance Steering-plane for Aeroplanes"), Max Goehler (US688408A then US997804A in 1910: "Propelling-vane for Flying-machines"), and Reginald Fessenden (e.g., US742780A then US1158124A in 1909: "Signaling Apparatus for Aerial Navigation"). See also Appendix Figure A4 for county-level maps of changes in aviation patent output.



(a) Patenting Intensity, 1894-1907



(b) Patenting Intensity, 1908-1913

Fig. 3. Geographic distribution of aviation patents, 1894–1907 and 1908–1913.
(a) Patenting intensity, 1894–1907.
(b) Patenting intensity, 1908–1913.

Table 4
Post proof-of-concept changes in aviation innovation output and the role of county characteristics.

DV = Aviation patents	(1)	(2)	(3)	(4)	(5)
Post Proof-of-concept	1.784*** (0.181)	2.119*** (0.131)	2.186*** (0.169)	1.938*** (0.194)	1.692*** (0.219)
Top quartile in Non-aviation patenting	1.015*** (0.200)			1.302*** (0.368)	
Post Proof-of-concept × top patenting	0.240 (0.188)			0.814*** (0.272)	0.849*** (0.327)
Top quartile in Manufacturing		0.229 (0.407)		−0.719 (0.528)	
Post Proof-of-concept × top manufacturing		−0.151 (0.148)		−0.268 (0.195)	−0.194 (0.180)
Top quartile in Population			0.524*** (0.199)	0.227 (0.304)	
Post Proof-of-concept × top population			−0.214 (0.178)	−0.508** (0.253)	−0.826*** (0.300)
Population(logged)	1.331*** (0.050)	1.441*** (0.065)	1.418*** (0.046)	1.379*** (0.053)	3.363*** (0.698)
County FE	No	No	No	No	Yes
Observations	57,440	57,440	57,440	57,440	9240
Counties	2872	2872	2872	2872	462
Log likelihood	−4322.67	−4415.79	−4408.03	−4267.53	−2346.64

Notes: Poisson regression coefficients with robust standard errors clustered at the county level in parentheses.
* $p < 0.1$.
** $p < 0.05$.
*** $p < 0.01$.

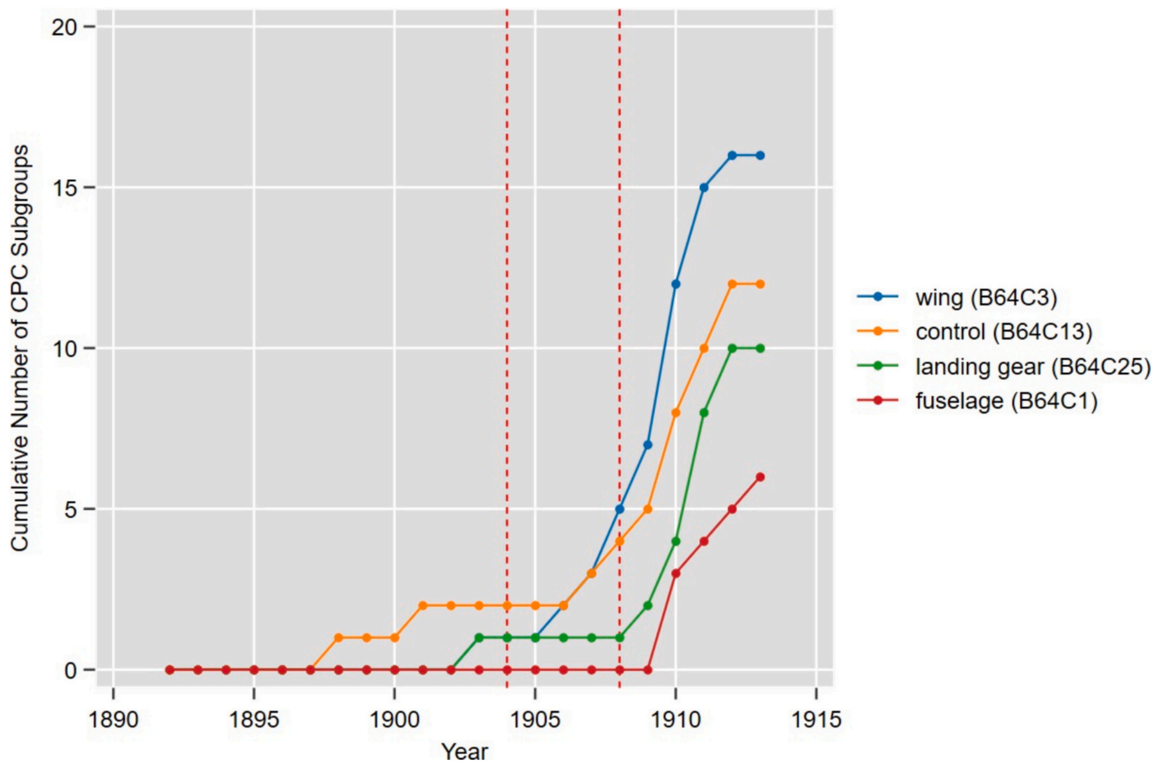


Fig. 4. Expansion of idea space: within airplane CPC subgroups, 1894–1913.

CPC subgroups that classify areas where primary components were being developed. In Fig. 4, we plot the cumulative number of CPC subgroups that existing for wing (B64C3), control (B64C13), landing gear (B64C25), and fuselage (B64C1) components of airplanes.

The CPC subgroup plots in Fig. 4 underscore that following proof-of-concept demonstration there was a rapid rise in the expansion of idea space within these components. This again suggests that innovators became more active in all dimensions of the airplane and were likely able to apply their existing capabilities to advance the technology by focusing on areas that were relatively unaddressed prior to proof-of-concept demonstration. Indeed, our review of archival material provides evidence that inventors who had previously not been working on aviation issues quickly turned to new types of innovations within the field of aviation after proof-of-concept demonstration.[24] Accordingly, we observe the creative recombination of existing and altogether novel solutions to more nuanced dimensions of the airplane.

Next, we consider the spillovers that proof-of-concept demonstration of the airplane may have had on alternative types of flying devices. While we have already observed that the demonstration of the fixed-wing airplane positively influenced aviation innovation, writ large, here we investigate if there were spillovers to the other types of flying devices. Specifically, we examine increases in patenting for lighter-than-air, ornithopter, and rotorcraft, which are conceptually and technologically distinct from the airplane but still within the broader category of flying machines. Fig. 5 provides plots of the by-year patent counts for these alternative aviation devices,[25] and Table 5 provides the estimated effect of proof-of-concept demonstration on fixed-wing airplane and alternative flying devices separately.

Fig. 5 shows increases in both fixed-wing airplane and alternative flying devices innovation starting in 1908, indicating positive spillovers onto these alternative types of aviation devices. This provides evidence that inventors not only became more interested in the airplane, but also that proof-of-concept demonstration encouraged innovators to engage with more technologically distant alternative designs within the broader aviation space, such as lighter-than-air, ornithopter, and rotorcraft devices.[26] This is corroborated by our results in Table 5, and we find a positive and significant effect for *Post Proof-of-Concept* across all model specifications, for both the fixed-wing airplane and alternative flying devices. Indeed, it is likely that the success of the airplane motivated inventors to intensify their efforts to try to make creative breakthroughs within in wider aviation domain. That is, the attention directed by the proof-of-concept demonstration of the airplane also encouraged potential innovators to work more on other types of flying machines. In 1909, for example, J. Newton Williams and Emilie Berliner conducted the first test-flight of an American designed "heavier-than-air flying machine, which depends on aerial screws for its lifting power" (Youngstown Vindicator, 1909)—a concept that would develop into a functioning helicopter two decades later.[27] Thus, in bringing the attention of innovators to the broader flying machine category, proof-of-concept demonstration appears to have fostered progress in aviation more widely, and some technological advances could enable progress in more one type of flying machine—such as engine construction addressing

[24] For example, we observe new types of wing structures (e.g., James Stephens in 1910: "Aeroplane Flying-machine" US1127105A), control systems (e.g., Edson Gallaudet in 1910: "System of Aeroplane Control" US1058422A), landing gear (e.g., George Otis Draper in 1909: "Landing and Starting Apparatus for Aeroplanes" US965881A) and airplane body and cabin designs (e.g., Francois Rilleau in 1911: "Aviator-protector" US1027764A) being filed in the years immediately after proof-of-concept demonstration of the airplane.

[25] See also Appendix Fig. A5 for changes in cumulative number of CPC subgroups within alternative flying devices.

[26] Examples of these include John Hafely's 1910 lighter-than-air "Screw-propelled Channeled Baloon" US997496A, John Emery Harriman Jr.'s ornithopter "Aeromobile" US1161664A, and James Beard's 1909 rotorcraft "Aerial Machine" US950427A.

[27] See also Emilie Berliner's later 1910 patent: "Helicopter" US1152268A.

power-to-weight performance and blade design.

With our results from the regional interactions in Table 5, we also observe that the counties with strong prior patenting experience had a significantly greater increase in fixed-wing airplane innovation after proof-of-concept demonstration (e.g., Model 4: $\beta = 1.229$; *95 % CI* = [0.178, 2.280]), but this did not appear to have as discernable of an impact on the alternative flying devices (e.g., Model 9: $\beta = 0.520$; *95 % CI* = [−0.294, 1.134]). While the confidence intervals of these two estimates overlap and we cannot make a definitive claim, this could suggest that fixed-wing airplane technologies were relatively more likely to advance on the basis of pre-existing experience following proof-of-concept. Possibly because proof-of-concept demonstration gave airplane inventors a new template to work with, those who began to innovate elsewhere in the aviation domain were less fruitful in incorporating their pre-existing knowledge in the pursuit of advancing alternative flying devices. Hence, it may be that outside-the-box individual creativity had a stronger role on these spillover aviation technologies to the extent that they could think about the problem of flight differently following the airplane demonstration. It is also the case that counties with strong pre-existing patenting capabilities might have had greater access to resources, including skilled engineers, funding, and infrastructure. These resources may have helped local inventors pursue more complex creative and resource-intensive innovation projects, which had their intricate issues become salient following the airplane's proof-of-concept demonstration.

4.2. Supplemental analyses

With our primary analyses, we show that aviation innovation in the United States was experiencing substantial growth during our window of observation, to which proof-of-concept demonstration plausibly played a critical role. In this section, we conduct supplemental analyses that allow us to better assess this main finding and provide an additional measure of robustness. In particular, we seek to help alleviate potential concerns that aviation innovation had already embarked on an upward trajectory before 1908, which could suggest that the post-1908 growth in patenting might have occurred independently of the demonstration. While we cannot necessarily rule out this possibility, or completely disentangle the effect of proof-of-concept demonstration from other possible influences, we seek to support our primary analyses by showing that the post-1908 growth in aviation innovation was uniquely stronger than that of counterfactual technologies and with those with a similar pre-trend prior to 1908. We use a synthetic difference-in-differences approach to construct such counterfactuals and re-estimate the effect of proof-of-concept demonstration on aviation patenting.

Arkhangelsky et al. (2021) show the theoretical and empirical robustness of synthetic difference-in-differences for causal estimates by establishing parallel pre-trends with a constructed counterfactual. Based upon this approach, we constructed two synthetic counterfactuals using non-aviation transportation-related technologies following Pailañir et al.'s (2022) *sdid* STATA procedure (see also Clarke et al., 2024). The first synthetic counterfactual was constructed using the annual patent counts of non-aviation transportation technologies such as automobile (B62D), carriages (B62C), railcars (B61C), and ships (B63B) (see, again, Fig. 1), among others.[28] The second synthetic counterfactual was constructed using technology subclasses with the closest pre-trend, CPC B61J and B61K,[29] which were given the greatest weights in the creation of the synthetic control group using all transportation technology classes. Selecting on this subset of technologies created a synthetic counterfactual with a very approximate pre-trend to that of aviation.[30]

Table 6 provides the results of this analysis, and Fig. 6 provides an illustration of our two synthetic counterfactuals plotted against aviation patenting output. We interpret the average treatment effect on the treated (ATT) result from the synthetic differences-in-differences as indicating that proof-of-concept demonstration led to a greater increase in aviation innovation output compared to other types of transportation technologies by about 210 patents (*95 % CI* = [91.22, 329.58]) and 226 patents (*95 % CI* = [89.27, 363.08]) in a given year on average, relative to the synthetic counterfactual. Annual patent counts of all transportation technologies were used in the construction of the counterfactual for Table 6a, while only B61J/B61K classes were used for Table 6b. With respect to the subclass counterfactual, this is roughly equivalent to an overall seven-fold increase compared to the pre-1908 average.[31] Fig. 6 underscores how this approach may help to mitigate the potential for different pre-trends to bias our estimates, and we observe relatively consistent patterns until there is a substantial growth of aviation patents starting in 1908.[32] This, ultimately, provides us with additional confidence that proof-of-concept demonstration of the airplane had a positive effect on aviation patenting in the United States and further helps to highlight the importance of this construct with respect to innovation and industry evolution.

5. Discussion

5.1. Generalizable insights related to proof-of-concept demonstration

Our article makes a key theoretical contribution with respect to its conceptualization of proof-of-concept demonstration. While we study this within the context of aviation innovation and the emergence of this particular industry, future researchers can further unpack proof-of-concept demonstration as a core construct—both in theories of technological progress and industry emergence, as well as within empirical studies of other technologies and industries. Future research may wish to consider conditions under which proof-of-concept demonstration occurs, as opposed to other emergence triggers, and compare the trajectories of innovation and industry formation. Likewise, exploiting heterogeneity in a focal technology will likely tell us a great deal about the importance of different factors that influence subsequent development. There are a variety of other counterfactuals worth examining. For example, the technological distance between the design used for proof-of-concept demonstration and the eventual commercial prototype or beta-testing models likely affects who innovates and what is being worked on. Thomas Edison's 1878 proof-of-concept demonstration of the incandescent light bulb at his Menlo Park, NJ laboratory helps

[28] These include 4-digit CPC subclasses under B60 (Vehicles in General), B61 (Railway Systems; Railway Vehicles), B62 (Land Vehicles for Traveling Otherwise than on Rails), B63 (Ships or Other Waterborne Vessels; Related Equipment) that pertain to transportation technologies: B60B, B60G, B60K, B60L, B60R, B60T, B61B, B61C, B61D, B61F, B61G, B61H, B61J, B61K, B61L, B62B, B62C, B62D, B63B, B67B.

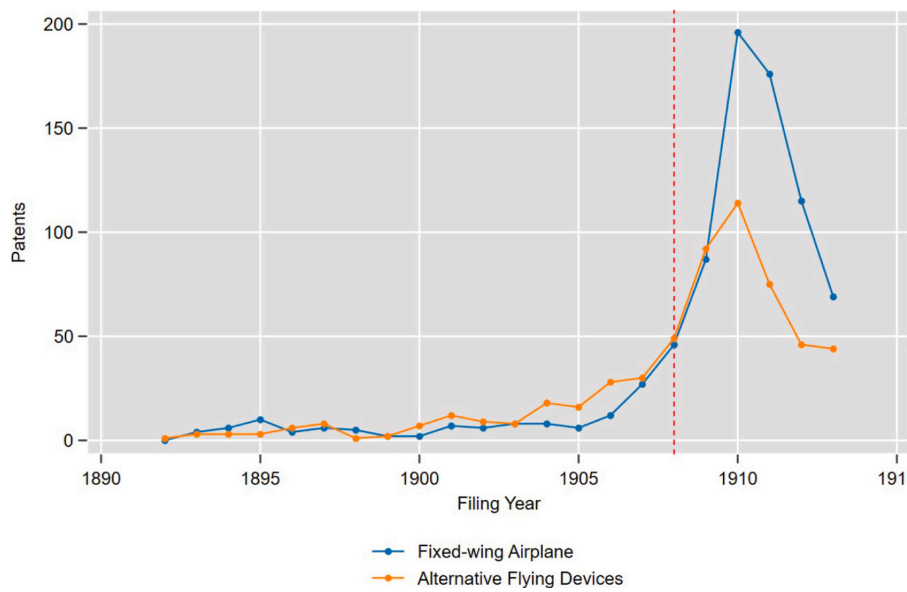
[29] B61K (Auxiliary Equipment Specially Adapted for Railways, Not Otherwise Provided For); B61J (Shifting or Shunting of Rail Vehicles).

[30] There can be several plausible reasons as to why these two classes had a very similar pre-trend with aviation innovation. While railcar designs had already stabilized by 1890s, the need for improved operational safety and efficiency became a bigger concern. For example, the Safety Appliance Act of 1893 was a landmark piece of legislation in the United States that mandated and significantly improved railroad safety. As rail traffic increased, the need for efficient methods to transfer passengers and freight, manage shunting operations, and ensure safety became paramount, driving innovation in B61K and B61J technologies.

[31] ATTs of 210 and 226 divided by 31.2, the pre-treatment mean.

[32] In an estimation strategy similar to Moser and Voena (2012), we used these technologies as a counterfactual, while using aviation technology as the treatment and incorporating synthetic weights from the STATA *sdid* command developed by Pailañir et al. (2022). The results in Appendix Table A3 appear consistent with our main results.

(a) Fixed-wing Airplane vs. Alternative Flying Devices



(b) Selected Examples of Alternative Flying Devices

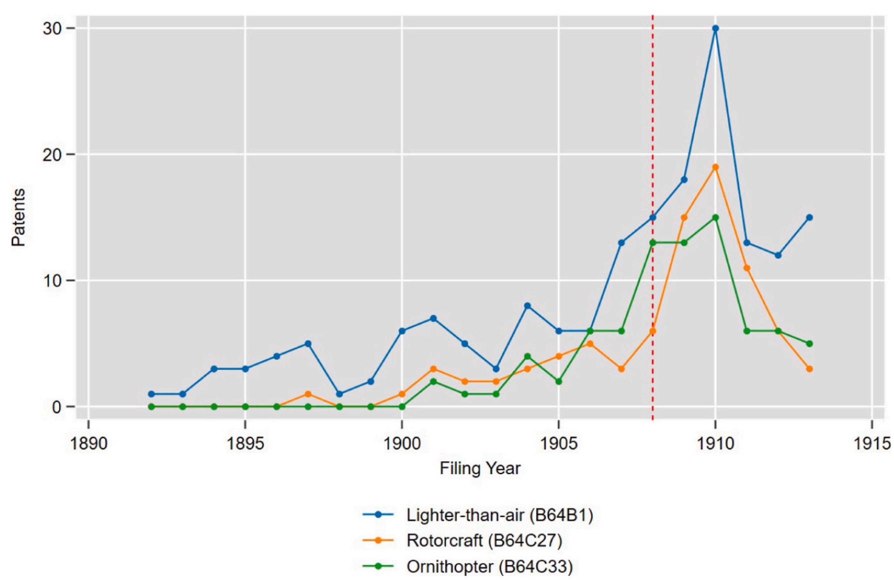


Fig. 5. Innovation spillovers: patenting for alternative flying devices, 1894-1913.
(a) Fixed-wing airplane vs. alternative flying devices.
(b) Selected examples of alternative flying devices.

illustrate this point, as well as how such events can facilitate the transition to commercialization by spurring the initiatives of value network actors.[33] A variety of companies, including Edison's, were already working out how to employ this new technology, and the first commercial instillations occurred in 1880 (*Sci. Am.,* 1880).

Beyond the historical examination of aviation innovation, our focus on proof-of-concept demonstration as a catalyst for creative and innovative output also speaks to issues that have clear contemporary relevance, and our theoretical framework offers insight into its potentially important ramifications. Consider, for example, other newly demonstrated technologies such as the recent release of generative artificial intellegence tools with respect to how this widespread shock directed the attention of those working in various domains to the potential for AI systems to revolutionize work (e.g., Rotman, 2023; Van Dis et al., 2023). Similarly, Boston Dynamics' video releases of their robots is likely to have spawned ideas for creative uses and innovations by others seeking to advance and ultimately provide commercial applications for these forms of robotic technologies (see Stern, 2024). Many blockchain technologies, too, have been advanced through proof-of-

[33] Notably, Edison's 1878 light bulb would last only minutes due to design limitations, and it was not until an 1879 public demonstration that he would provide a model that could function for a significant length of time following his further technological advances with carbon filaments (Burton, 2023).

Table 5
Post proof-of-concept changes in fixed-wing airplane innovation vs. alternative flying devices innovation.

DV = Aviation patents	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
	Fixed-wing airplane					Alternative flying devices				
Post Proof-of-concept	1.853***	2.444***	2.297***	1.939***	1.688***	1.682***	1.850***	1.984***	1.844***	1.455***
	(0.297)	(0.279)	(0.300)	(0.336)	(0.399)	(0.304)	(0.223)	(0.244)	(0.299)	(0.359)
Top quartile in non-aviation patenting	0.844***			1.108**		1.074***			1.393***	
	(0.298)			(0.552)		(0.308)			(0.420)	
Post Proof-of-concept × top patenting	0.655**			1.229**	1.024*	−0.155			0.520	0.788
	(0.317)			(0.536)	(0.583)	(0.318)			(0.415)	(0.598)
Top quartile in manufacturing		0.152		−0.521			0.293		−0.643	
		(0.420)		(0.564)			(0.365)		(0.439)	
Post Proof-of-concept × top manufacturing		−0.010		−0.557	−0.293		−0.375		−0.234	−0.298
		(0.310)		(0.399)	(0.332)		(0.243)		(0.326)	(0.287)
Top quartile in population			0.321	0.007				0.454	0.046	
			(0.322)	(0.353)				(0.281)	(0.435)	
Post Proof-of-concept × top population			0.159	−0.156	−0.409			−0.513*	−0.660	−1.000*
			(0.320)	(0.379)	(0.487)			(0.263)	(0.429)	(0.528)
Population(logged)	1.317***	1.434***	1.407***	1.367***	3.425***	1.328***	1.432***	1.426***	1.384***	3.517***
	(0.057)	(0.072)	(0.050)	(0.060)	(0.784)	(0.052)	(0.058)	(0.048)	(0.054)	(1.032)
County FE	No	No	No	No	Yes	No	No	No	No	Yes
Observations	57,440	57,440	57,440	57,440	5300	57,440	57,440	57,440	57,440	4060
Counties	2872	2872	2872	2872	265	2872	2872	2872	2872	203
Log likelihood	−2122.85	−2170.77	−2166.08	−2098.24	−1086.07	−1866.03	−1885.08	−1884.32	−1848.30	−961.51

Notes: Poisson regression coefficients with robust standard errors clustered at the county level in parentheses.
* $p < 0.1$.
** $p < 0.05$.
*** $p < 0.01$.

Table 6
Synthetic difference-in-differences estimation of post proof-of-concept.

(a) Synthetic counterfactual using all transportation technologies.

	ATT	Std. Err.	t	P > t	[95 % Conf. Interval]	
Post proof-of-concept	210.402	60.806	3.46	0.001	91.225	329.579

(b) Synthetic counterfactual using B61J and B61K technologies only.

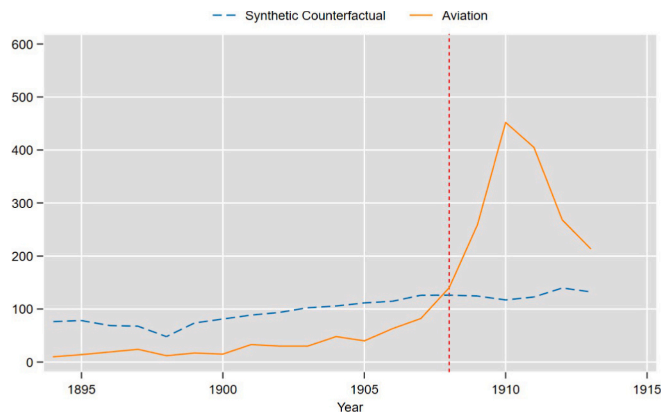
	ATT	Std. Err.	t	P > t	[95 % Conf. Interval]	
Post proof-of-concept	226.178	69.850	3.24	0.001	89.273	363.082

concept demonstration, which has encouraged widespread discussion about opportunities for future development and potential applications for their use (e.g., Hsieh et al., 2018). We can extend the framework and ideas presented in this research to propose that future creative output and innovation in such technologies may be shaped by proof-of-concept demonstration and other similar events that promote the demonstration of emerging technologies (e.g., Frey and Gallus, 2017; Gallus and Frey, 2016; Galasso et al., 2018), such as the DARPA Grand Challenges autonomous vehicle race (e.g., Sohn et al., 2024b). It may also be the case that the public display of a new technology can be strategically employed to encourage the development of complementary products that support a technological ecosystem (e.g., Kapoor and Agarwal, 2017).

Future research also needs to consider the nature of the underlying technology when addressing how proof-of-concept demonstration may affect the locus and trajectory of innovation, and there is already a rich literature on the topic that is likely to be pertinent. For example, we know from prior work that enhanced access to knowledge and information (e.g., Agrawal et al., 2017), general and specific resources (Sohn et al., 2024a), or advocacy and incentives (Olsen et al., 2016) can spur creative and innovative output. For the purpose of generalizability and understanding processes of industry evolution, it is also important that we highlight that the entire system needs to be considered because second-order effects may play a significant role in determining how technologies develop. Thus, our insights from this article may also serve to complement related work that has suggested prescriptions for organizations seeking to enhance their creative and innovative output (e.g., Amabile and Fisher, 2012; Calic et al., 2022; Khessina et al., 2018). However, systems of incentives for individuals and organizations may change overtime and industries evolve, and this may affect creative outcomes (e.g., Azoulay et al., 2011; Bradler et al., 2019; Charness and Grieco, 2019; Chen et al., 2012; Erat and Gneezy, 2016; Gross, 2020). These issues are undoubtedly complex and contingent on many factors that are context dependent. Nevertheless, we expect that our article can stimulate new research and help bridge micro- and micro-level disciplinary divides that will allow scholars, practitioners, and policymakers to better understand the various creative and innovative outcomes that emerge from different types of technological advances.

With respect to industry emergence and evolution, the results of our analyses align with the industry incubation stage framework proposed by Agarwal et al. (2017). Accordingly, this work provides a rich case study of this understudied element of industry emergence around a new technology, and our conceptualization of proof-of-concept demonstration as a triggering event provides additional nuance to our current understanding of key actors and actions underpinning technological advances during this stage (see also Aversa et al., 2022b). Notably, considering our context and the subsequent development of the practical airplane, proof-of-concept demonstration is just one of the triggers that may shape innovative activity, as other scientific discoveries, unmet user needs, and mission-orientated factors all may lead to key developments for a new technology. While this also highlights the complexity of innovation in the incubation stage, it underscores the value of studies that take a holistic look at how industries emerge around focal technologies, and it provides insights into how future research can address open questions that span levels of analysis within these domains.

(a) Aviation Technology vs. Counterfactual (All Transportation Technologies)



(b) Aviation Technology vs. Counterfactual (B61J and B61K Only)

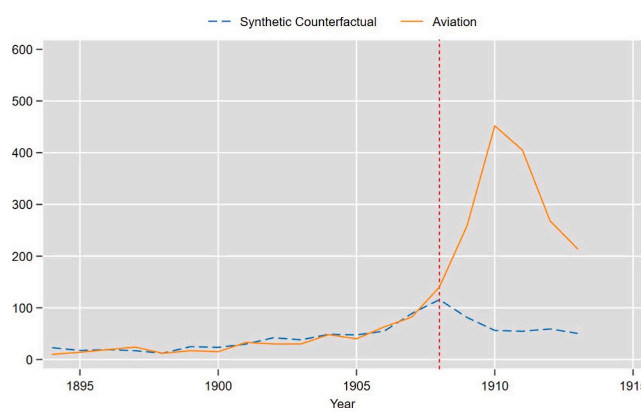


Fig. 6. Synthetic difference-in-differences: aviation technology vs. counterfactual.
(a) Aviation technology vs. counterfactual (all transportation technologies).
(b) Aviation technology vs. counterfactual (B61J and B61K only).

5.2. Additional considerations within the context of aviation

Given our case study's focus on the period immediately around the invention of the airplane (i.e., 1894–1913), we have thus far only touched on the general implications of proof-of-concept demonstration with respect to IP considerations. This, however, plays a much more central role in the empirical setting during the subsequent decade. As noted earlier, we expect that proof-of-concept demonstrations are more likely to occur when IP protections are strong and can be strategic if they encourage others to build off a demonstrated concept, but that strong IP protection may have a less straightforward overarching effect on subsequent commercialization and industry development (see also Boldrin and Levine, 2008; Jaffe and Lerner, 2004). Indeed, this appears consistent with what plays out after our period of study. The Wrights filed lawsuits against competitors working on airplane design, and the first of these lawsuits (Wright Co. v. Herring-Curtiss Co. (Wright III), 204 F. 597, 597–614 (D.C.W.D.N.Y. 1913), *aff'd per curiam* 211 F 597, 654–55 (2d Cir. 1914) (Wright IV)) was ruled in their favor in 1913, and the appeal of that decision was finally decided in 1914 in the favor of the Wrights (see Johnson, 2004). It was not until the 1917 Manufacturers Aircraft Association patent pool, which was encouraged by the United States government to support the production of aircraft for World War I, that a more clear developmental ecosystem for aviation technological progress emerged.[34] An ample body of cross-disciplinary research in this area provides insight into a variety of important issues and debates about the effects of the patent wars and patent pool on airplane innovation and the aviation industry (e.g., Barnett, 2015; Bittlingmayer, 1988; Bryan, 2023; Katznelson and Howells, 2015). For the purpose of our study, however, it is possible that IP protections have downward biased the effect in proof-of-concept demonstration for some of the latter years' estimates. Other scholars bring up related and interesting perspectives about the counterfactual of how technological progress on the airplane could have advanced in the United States. For example, Boldrin and Levine (2008) highlight that had the Wright's proof-of-concept demonstration occurred earlier (the Wrights obtained their patent in 1906), this could have led to greater progress on the airplane: "they were capable of building an airplane or teaching other people how to do it, but they did not. Further, even after the patent was granted, rather than take advantage of their legal monopoly by developing, promoting, and selling the airplane, the Wright brothers kept it under wraps, refusing for a couple of more years to show it to prospective purchasers" (p. 87). An implication of this, as our data and analyses show, is that more widespread engagement with aviation innovation in the United States was effectively delayed until after proof-of-concept demonstration took place in 1908.

Explaining why different outcomes did not occur is also especially crucial when considering the managerial and policy implications of our work. Bryan (2023), in particular, helps speak to this issue in considering why the early airplane industry became dominant in Europe despite the first flight having occurred in the United States (see also Mowery and Simcoe, 2002). His work addresses earlier studies the have pointed to either patent hold-up[35] (e.g., Shulman, 2002) or the lack of government subsidies (e.g., Crouch, 2003) as possible factors limiting aircraft development (see also Barnett, 2015; Katznelson and Howells, 2015), and he provides a novel framework indicating that it was a lack of complementary technology "microinventions" hindered the development of an American aviation industry relative to Europe. Our works, in conjunction, provide meaningful groundwork for future scholars to address how and why new industries form when and where they do (e.g., Aversa et al., 2022b), especially with respect to the role of technological progress. Moreover, our works speaks to the importance of reconsidering historical settings with new theory and data (e.g., Mendonça, 2013; Sokoloff, 1988), which can provide a deeper understanding of key issues that may have been underappreciated by prior scholarship on a topic (e.g., Agarwal et al., 2017; Cattani, 2005; Comino et al., 2020; Giorcelli and Moser, 2020; Greenberg et al., 2024; Mokyr, 2011; Moser, 2005; Taalbi, 2017).

While we have focused on the incubation stage of the aviation industry's emergence (i.e., before the aviation industry emerged, solidified, and commercialized in the United States), it is important for us to note that there are still ample opportunities to understand the role of creativity and innovation in later periods as well. Beyond the touring exhibitions that were precursors to barnstorming, airplanes did not find their first serious wide-spread application until World War I (see also Maurer, 1978). In the early years of the war, planes were predominantly

[34] While well beyond the scope of this work, we note that government intervention and IP protection in American aviation experienced substantial additional changes over the following decades (see Bittlingmayer, 1988; Hanlon and Jaworski, 2022; Lampe and Moser, 2016; Mowery, 2015; Sohn et al., 2024a).

[35] This appears generally consistent with Boldrin and Levine's (2008; see also Boldrin and Levine, 2013) conjecture that the breadth of the Wright's patent claim could have hindered aviation development in the United States, given that Glen Curtiss' innovations in "movable control surfaces" (the basis of more modern airplane control systems) were distinct from the Wright's "wing warping" (p. 206–207). They, too, point to Europe as a counterfactual for American technological progress in aviation (p. 87–88).

assigned to reconnaissance roles, but by the end of the war, designs were adapted to meet the needs of the evolving battlefield and new types of planes were developed and being used for bombings and in air-to-air combat. Progress on aviation was certainly global by this era, and as Bryan (2023) points out, the trajectory of innovation in different may have diverged at the very early stages of industry emergence. Especially considering that some European countries were already in an arms race well prior to World War I, it is plausible that government interventions shaped technological progress there, which warrants its own investigation. Even in the United States, the Army provided a sizable grant for Smithsonian Institute Secretary Samuel Langley to continue progress on his Aerodrome—a project that he abandoned after two failed attempts to fly in October and December 1903 (McFarland, 1997, p. 2). These developments are beyond the scope of this work (see also Frenken, 2000), but they suggest an important line of inquiry pertaining to the civil-military-government nexus and technological progress.

5.3. Bringing together micro and macro perspectives in creativity and innovation

Our use of patent data and examination of their content allows us to link our empirics with the underlying logic of creative output that has been increasingly interdisciplinary but is still often siloed by disciplinary perspectives. Indeed, there is a great amount of inherent overlap and opportunities to learn from each other's research, even if micro-level creative behavior and macro-level innovation outcomes are often studied separately due to the focus of different disciplines. The creativity literature in psychology has emphasized, in particular, that the definition of creative output is something that is both novel and useful (Harvey and Berry, 2023). Perhaps unsurprisingly, this closely maps onto dimensions that make up the criteria for patenting, and it further indicates how proof-of-concept demonstration likely enhances inventors' perceptions of a technology's usefulness. And although we chose patents as a pragmatic measure of innovative output, we are also careful to acknowledge that patents may only capture a portion of the innovative activity taking place in the aviation industry during this time (see also Moser, 2016), and other approaches are likely needed to fully understand creativity and innovation across contexts. For example, we do not capture all of the creative ideas that people were bringing forth when thinking about what they could do with this emerging aviation technology.[36] Nevertheless, we expect that our extensive use of specific archival material has helped to contextualize technological progress during our period of study, which ultimately provides us with a richer base of interdisciplinary knowledge about these issues.

We also wish to highlight that sociologists have pointed to the need to better understand distinct structures, institutions, and contexts as antecedents, along with audiences, perceptions, and evaluations as consequences of creativity (Godart et al., 2020, p. 490). Prior research has indeed shown that a variety of social issues can affect creativity and innovation (e.g., Vakili and Zhang, 2018). These are likely relevant issues for studies related to ours, even if they are not key considerations of this work. Bryan's (2023) comparison of American and European aviation micro-inventions, for example, helps build a connection to recent works that have investigated how cultural factors can facilitate or hinder creativity and innovation (see also Chua et al., 2015; Ibert and Müller, 2015; Shane et al., 1995). Such dimensions may mediate the type of effects that matter to both scholars of creativity and innovation, and we suspect that future scholarship would benefit from additional cross-disciplinary dialogue in this space.

Considering the inferences provided by this article, it is likely that contextual elements such as social structure and institutions play a significant role in shaping both the likelihood of proof-of-concept demonstration occurring and subsequent responses of actors. As we noted earlier, the effect of patent disputes on innovation may be downward biasing the effects we observe in our setting relative to a different setting or when using an alternative operationalization of creative output (see also Barnett, 2015; Boldrin and Levine, 2008). Other related considerations, such as the curvilinear relationship between creativity and competition (e.g., Gross, 2020), may also be especially relevant for extending the framework provided in this article to different empirical contexts and for enhancing cross-disciplinary dialogue. Accordingly, scholars wishing to map out the technological development of a technology over a longer timeframe, such as in post industry emergence phases, may want to consider the roles of IP rights, competitive dynamics, and other institutional factors in addition to the social norms governing innovative activity. This further underscores that there are ample opportunities for future research to make headway on a variety of important issues related to proof-of-concept demonstration, creativity and innovation, and industry emergence around new technologies.

6. Conclusion

Ultimately, our article provides several key insights that enhance our knowledge about creative processes that underpin innovation and industry formation around new technologies. Theoretically, we underscore how proof-of-concept demonstration can shape the trajectory and locus of innovation, which adds nuance to our understanding of the triggers of industry emergence during its incubation stage. Our historical case study of early aviation in the United States provides a detailed investigation of how the first powered flights led to significant changes in innovative output and content. We leverage archival material and novel data, that we make available to other researchers, to detail who patented, what was being developed, and where technological progress in aviation occurred during the late 19th and early 20th centuries. Accordingly, our work bridges micro- and macro- levels of analysis and perspectives to provide a dynamic and comprehensive account the invention of the airplane, which allows for a deeper understanding of creativity, innovation, and the emergence of industries around new technologies. We expect that this research will help provide a foundation for future cross-disciplinary scholarship to continue to examine these issues and also provide insights for managers and policymakers who have pragmatic interest in processes of technological progress.

CRediT authorship contribution statement

Daniel B. Sands: Writing – review & editing, Writing – original draft, Methodology, Data curation, Conceptualization. **Eunhee Sohn:** Writing – review & editing, Writing – original draft, Methodology, Data curation, Conceptualization. **Robert Seamans:** Writing – review & editing, Writing – original draft, Methodology, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.respol.2025.105230.

Data availability

Data will be made available on request.

[36] Perhaps alluding to this is the dramatic increase in count of "aeroplane" and "flying-machine" references made in newspapers after proof-of-concept demonstration; see Appendix Figure A6.

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