

## Prizes, patents and the search for longitude<sup>☆</sup>

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### ABSTRACT

The 1714 Longitude Act created the Board of Longitude to administer a large monetary prize and progress payments for the precise determination of a ship's longitude. However, the prize did not prohibit patenting. We use a new dataset of marine chronometer inventors to show that the propensity to patent was high. We argue that while the prize spurred entry by key inventors, and progress payments facilitated research investment in an area of significant social value, patents promoted disclosure. Our findings highlight the importance of complementarities between prize and patent-based incentives in the design of innovation inducement contests.

### 1. Introduction

In response to a prominent navigation disaster and growing demand for a solution to the problem of identifying a ship's position at sea, a 1714 British Act of Parliament created a substantial award for the precise determination of longitude.<sup>1</sup> Using a prize of up to £20,000 (around £2.5 million today) a commission of adjudicating experts (the Board of Longitude) and resources for inventors to engage in experimentation, the government aimed to encourage knowledge accumulation in an area of high social value but relatively low private investment. By the early 1770s following a long and acrimonious dispute with the Board of Longitude, John Harrison (1693–1776), an English clockmaker, was awarded monetary values approximately equivalent to the prize.<sup>2</sup> Mokyr (2010, p. 42) describes Harrison's marine chronometer as "one of the epochal innovations of the eighteenth century."

The longitude prize is frequently cited in the innovation literature as a prominent example of a non-patent based mechanism designed to spur technological development (Wright, 1983; Kremer, 1998; Kalil, 2006; Kremer and Williams, 2010, 2012; Brunt et al. 2012; Moser and Nicholas, 2013; Murray et al. 2014). It has motivated a range of modern prize competitions such as the recent X-Prize contests for space innovation, developments in super-efficient vehicles or cost-effective gene sequencing. The America COMPETES Act passed by Congress in 2010 provides Federal agencies with the necessary authority to conduct prize competitions.

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<sup>1</sup> In 1707 during the War of the Spanish Succession, Admiral Sir Cloudesley Shovell led a fleet of British naval ships back to England from Gibraltar but the fleet lost its position in fog around the Isles of Scilly off the Cornish peninsula of Britain, leading to the loss of four ships and almost 2000 lives. Also, in July 1713 two mathematicians William Whiston and Humphrey Ditton published an idea in *The Guardian* newspaper whereby ships in set locations in sea trade channels would explode a mortar at a set height and time to allow location by other ships to be determined by calculating the time elapsing between the explosion flash and the corresponding sound. They also engineered a petition submitted to Parliament seeking to establish an award for a method to establish longitude.

<sup>2</sup> It is important to note that the longitude prize was not actually awarded. The monetary amounts given to Harrison represented only a tacit admission that the navigational problem had been solved.

In the spirit of the 1714 Act, the 2014 Longitude Prize supported by the British government consists of a £10 million prize fund in an effort to solve the problem of global antibiotic resistance. This is an area with substantial social value that has not been addressed through patent-based incentives.

We examine the effect of the longitude prize and the patent system on the process of technological development. We use a new dataset of chronometer inventors assembled from *Chronometer Makers of the World* (CMW) compiled by Tony Mercer (1919–2012), the grandson of the founder of Thomas Mercer Ltd., a prominent English watch and chronometer manufacturer established in London in 1858. These new data are novel and informative. Several studies have analyzed the search for longitude from an historical or a legal perspective (e.g., Sobel, 1996; Siegel, 2009), but quantitative analysis has been lacking. While Harrison's efforts are especially well-documented, and there is considerable debate about the Board of Longitude's decision to refuse payment to him (e.g., Betts, 1996), no empirical analysis has been conducted on the inventors who actually developed marine chronometers.

An advantage of our data is that we can examine the full life cycle of the industry. The period we consider from 1714 to 1939 covers the duration of the prize competition under the Board of Longitude, the rise of the industry as “the British turned the marine chronometer into an object of industrial manufacture and commercial use” (Landes, 1998, p. 171), and its interwar decline when radio signals displaced navigation by chronometers. Moreover, because the longitude prize did not preclude patenting, we are able to take a long run perspective on the development of the chronometer in the context of the interplay between prizes and patents. For this purpose we hand-matched CMW entries against a data base containing all British patents granted from 1714 to 1939 to determine the extent to which inventors used the patent system.

Our empirical analysis has four main parts. First, we analyze the extent to which the Board of Longitude was able to spur the effort of inventors. We show that the monetary prize offered by the British government encouraged entry and led to intense competition by a small group of key inventors, including John Harrison. At the same time, we show that the number of active chronometer makers and craftsmen did not peak until the 1870s and 1880s, more than 150 years after the Longitude Act had been passed. We argue that the prize initiated a protracted process of cumulative innovation as the marine chronometer design was perfected over time.

Second, we show that the Board of Longitude paid out a substantial amount in interim progress payments to inventors for successful developments. These payments, totaling £52,535 or around £6.6 million today, are often neglected in the literature, but they provided crucial capital for research investment, improvement and experimentation. For example, Harrison received a series of payments in-between his first marine chronometer (called H1) completed in 1735 and his final H4 chronometer completed in 1759. Interestingly, however, we show that these progress payments do not predict the timing of entry or patenting. That is, the progress payments likely changed the allocation of resources to innovation for individuals like Harrison, but they did not increase the underlying supply of inventors or patents more generally.

Third, we examine the determinants of patenting in the cross section of inventors during, and after, the Board of Longitude era. We find a particularly high propensity to patent among marine chronometer inventors relative to benchmarks in the literature. In line with recent work on the British patent system (Bottomley, 2014), we argue that patents had private benefits by helping inventors to appropriate from their ideas while being socially beneficial by promoting the disclosure of useful knowledge. Notably, inventors like Harrison who opted to use secrecy, impeded the Board's efforts to ensure knowledge diffusion across innovators.

Finally, we show that prize and patent-based incentives continued to be important at a time when further developments to chronometers to improve accuracy became a focus of attention. Between 1823 and 1835, prize competitions conducted by the British Admiralty at the Royal Observatory in Greenwich to promote cumulative improvements to Harrison's basic marine chronometer design coincide with a large spike in the level of patenting. Difference-in-difference estimates suggest that the mean number of chronometer patents increased by between 59 and 174 percent during the 1820s and 1830s relative to a control group of scientific instrument patents.

Overall we argue that the development of the marine chronometer reflected a complementary relationship between prize and patent-based incentives. One measure of a prize competition's impact is its ability to change the allocation of resources to problem-solving. Our evidence suggests that the longitude prize provided a catalyst for skilled inventors to direct their efforts towards solving the longitude problem because patents alone had not generated sufficient incentives for private investment. On the other hand, because the patent system mandated inventors to disclose, we maintain that it corrected for a defect in the design of the longitude prize, where a lack of disclosure created a barrier to incremental invention. An extensive body of theoretical work on innovation has discussed the efficiency of using prizes as substitutes to remove the deadweight loss associated with patents (e.g., Wright, 1983; Kremer, 1998; Chari et al. 2012). We emphasize the potential significance of attributes like disclosure, which are already built into patents, in the design of innovation inducement policies.

The remainder of the paper is structured as follows. In the next section we provide a brief historical background on the longitude prize. Section three describes our dataset. Section four presents our analysis of the effect of the Board of Longitude's progress payments. Section five focuses on the propensity of inventors to patent chronometer inventions and on inventor-level determinants of patenting. Section six provides further evidence on the relationship between prizes and patents. Section seven concludes.

## 2. Historical background: aspects of the longitude prize

The British were not the first to offer a prize for longitude. The race for global trade and maritime supremacy led the Spanish monarchy to offer a prize for the discovery of longitude at sea during the late 1590s, to be followed in the early 1600s by the Dutch

Republic's sequence of prizes for finding "the East and West" (Davids, 2011).<sup>3</sup> The British government's 1714 decision to offer a particularly large award indicated the ongoing significance of efforts to address a navigational problem that, if solved, would have a substantial impact on welfare.

The Longitude Act of 1714 authorized the following payments to be made to anyone regardless of nationality: £10,000 for a method that could determine longitude within one degree, £15,000 if it was determined within two-thirds of one degree and £20,000 for positioning within half a degree.<sup>4</sup> Although it is not known how the government arrived at these "shadow prices" for innovation, it is clear that the Act created a premier targeted (i.e., *ex ante*) prize.

At the time of the Longitude Act measuring latitude involved using a simple scientific instrument (a sextant) to observe the angle between the horizon and a known celestial object such as the Sun or the North Star. Finding longitude was far more complex.<sup>5</sup> Although the theory was well-known (every 24 h the earth turns through 360 degrees, so each 15 degrees of longitude corresponds to a time-difference of one hour) without highly accurate sea-based timekeeping it was impossible to compare the local time with the time at a reference point.

Longitude could potentially be identified by a variety of celestial methods, such as eclipses of Jupiter's satellites. However in 1713 Sir Isaac Newton (1643–1727) pointed out that the lunar approach of measuring the distance between the moon and a fixed star would establish the location of a ship only to within two or three degrees – about 138–207 miles at the equator. This level of error was not much better than navigating by the rudimentary method of dead-reckoning (Gould, 2013).<sup>6</sup> Newton suggested that a time keeper was the most promising potential solution, but he also noted significant technical challenges associated with producing a time-piece that would be sufficiently accurate in the face of temperature, pressure and humidity variation at sea.<sup>7</sup>

The longitude prize had three key design elements of importance to our analysis. First, the Act created the Board of Longitude, a 23 person body of elites like the President of the Royal Society and the Speaker of the House of Commons, who ultimately met about three or four times a year, typically at the Admiralty Building in London. As a consequence of a key member, the Astronomer Royal Nevil Maskelyne (1732–1811), the Board generally favored "high-science" celestial methods relative to "low-science" mechanical solutions, like the one proposed by Harrison. At the Board's discretion awards could be made or withheld according to the criteria stipulated in the Act. With majority agreement one half of an award could be paid out, with the remainder held back until the method had been scientifically assessed on a voyage from a British port to a port in the West Indies. Further Acts were passed between 1714 and 1828 to promote additional areas in need of improvement, clarify the powers of the Board and the conditions of the longitude award. The Board was finally dissolved by an Act of Parliament in 1828.

Second, the Board of Longitude provided progress payments. The 1714 Act stipulated a sum not exceeding £2000 could be sanctioned by a quorum of five Board members for inventors making significant breakthroughs or interim research and development, but larger amounts were also paid out. For example, Leonhard Euler (1707–1783) received £300 in 1765 for his contribution to Tobias Mayer's lunar tables but Mayer's widow received £3000 the same year as a posthumous award for her husband's work. Importantly, the amounts paid by the Board were counted against the value of the 1714 prize. In Harrison's case he received £23,050 in a sequence of installments over more than three decades, which included the amount provided to him to construct his chronometers (Gould, 2013, p. 67). During its 114 year existence the Board of Longitude spent about £157,000 on items such as salaries for administrators and expeditions. About one-third can be attributed to progress payments and prizes (Howse, 1998).

Third, the prize did not substitute for patenting, but rather created an additional layer of incentives on top of the patent system. Notwithstanding the concept of intellectual property was still rudimentary at the time, a means of establishing proprietary rights over invention did exist in Britain (MacLeod, 1988). The 1624 Statute of Monopolies provided the basis of British patent law until the 1852 Patent Law Amendment Act was passed (Aplin and Davis, 2013). Although the 1624 Statute did not require detailed disclosure for a 14 year patent term, by the 1720s comprehensive written descriptions had become the norm and they were widely diffused.<sup>8</sup> Bottomley (2014, p. 28) describes patent specifications as being "diligently prepared, at least from the 1770s" and reflecting "a uniquely reliable corpus of cutting edge technology."

### 3. Data construction and summary statistics

Our empirical analysis is based on a dataset of chronometer inventors compiled from *Chronometer Makers of the World*, which

<sup>3</sup> Phillip II initiated the prize offer in 1597 which was formalized by Phillip III in 1598 as a prize of 6000 ducats plus an annual annuity of 2000 ducats and a gratuity of 1000 more. In 1600 the States General of the United Provinces of the Dutch Republic offered a prize of 5,00 guilders plus an annual annuity of 1000 guilders. The Dutch raised the prize amount to as much as 50,000 guilders by 1738, although there is some uncertainty in the historical record concerning the exact amount of the prize award (Gould, 2013, p. 12). Assuming this latter amount is accurate, it would be equivalent to about £450,000 today.

<sup>4</sup> At the equator each degree of longitude is approximately 69 miles converging to zero miles at the poles.

<sup>5</sup> A sextant measures the angle between two objects. At night, with clear skies, a navigator could determine a ship's latitude by the angle between the horizon and the North Star. The North Star is directly overhead the North Pole at an angle of 90 degrees north latitude whereas at the Equator it is at zero degrees latitude. During daytime the angle of the Sun above the horizon at noon could be used along with nautical almanacs to correct for the Sun's declination.

<sup>6</sup> Dead-reckoning involves using calculations about direction and distance traveled to pinpoint location, but is complicated by the effects of factors such as wind drift and tide.

<sup>7</sup> Newton stated: "[F]or determining the Longitude at Sea, there have been several Projects, true in the Theory but difficult to execute[.] One is by a Watch to keep time exactly[.] But by reason of the Motion of a Ship, the variation of Heat and Cold, Wet and Dry, and the Difference of Gravity in different Latitudes, such a Watch hath not yet been made" (Gould, 2013, p. 13).

<sup>8</sup> The famous 1778 *Liardet v. Johnson* case established that the specification should include disclosures to allow anyone skilled in the art to be able to replicate the invention.

according to its author represents “a comprehensive list of makers and craftsmen... who worked in the industry, their places of work and dates and serial numbers of their instruments.” Mercer compiled the data using records archived at Thomas Mercer Ltd and using other sources including firm archives, records of the British Admiralty and the British Horological Institute. His data include government and public institutions like the British Ministry of Munitions established in 1915, which we exclude in our analysis because they were end users rather than inventors or developers of marine chronometers. Further data cleaning produced a dataset of 1336 observations from the original 1701 entries in CMW.

**Table 1** shows descriptive statistics for the Board of Longitude era (1714–1828), the post Board era (1829–1939) and the life cycle of the industry (1714–1939). Entry and exit are defined in CMW by “dates of occupation” – when activity in the industry started and stopped. Although the list includes entry years up to 2006, in most of our analysis we truncate the data on the entry side to be between 1714 and 1939. Mercer acknowledges a drop in data quality around 1939 as records were lost during the Second World War. Entry and exit are provided in the majority of cases but to maximize use of the data, we linearly interpolated when one was missing. An active career was around 26 years for individuals. By comparison Khan (2015) finds an average career length of 18 years for a pre-1820 cohort of famous British inventors. For firms in CMW (about one third of the data), we find that an active period was around 44 years.

The longitude prize was a “public reward” that was open to inventors of any nationality. CMWs coverage is global, including chronometer makers like Pierre Le Roy (1717–1785) and Ferdinand Berthoud (1727–1807), two prominent innovators and rivals residing in Paris. Outside of Britain, 23 countries are represented, with the largest concentrations in France, Switzerland the U.S. and Germany. Moreover, the contest was not restricted to experts, so its design was analogous to the modern crowd sourcing tournaments examined by Boudreau et al. (2011). They show that if the problem to be solved is particularly difficult, opening up to a broad array of entrants can elicit the production of high-value long-tail ideas beyond what could be achieved by restricting the tournament to domain experts alone. Widespread entry meant that the longitude prize attracted practically-oriented inventors like Harrison, not just experts in celestial methods.

**Fig. 1** shows the location of the makers and craftsmen within Europe. Britain was a key location accounting for at least 70 percent of the entries with clustering in London, the county of Lancashire, and in cities along the south and northeast coast. These clusters are consistent with a division of labor in watch making (Ó Gráda and Kelly, forthcoming). In 1800, 70,000 workers were employed in the industry, mostly in Clerkenwell, London where final assembly took place (*New Scientist*, 1957). Specialist craftsmen in Lancashire produced tools and partly finished watch movements for the London market. Harrison's early experiments culminating in H1 were conducted in Barton-upon-Humber, in North Lincolnshire, but less than 3 percent of CMW entries were located within 50 miles of there. Harrison moved to London in 1730.

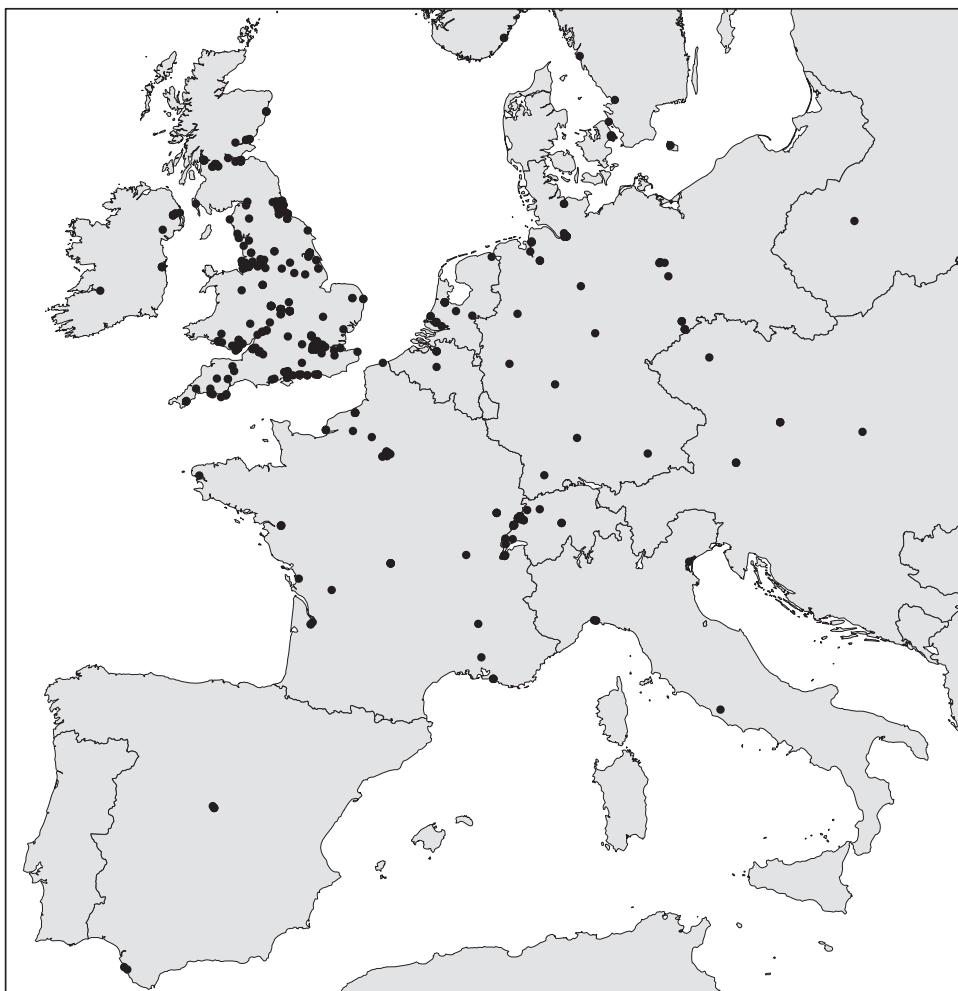
Chronometers varied by the quality of craftsmanship. To construct a quality indicator we used information in CMW to identify if the individual or firm listed supplied the Admiralty. According to Mercer (1991, p. ix) “a marine chronometer was of no value whatsoever until it had passed the exacting tests laid down by the British Admiralty.” In 1805 the Admiralty instigated a formal plan requiring that chronometers could only be sold to the public when they had been officially tested. The best chronometer makers were permitted to use the prestigious title of “Maker to the Admiralty” which was used in advertisements to aid appropriability (Ishibashi, 2013). During the Board of Longitude era, 35 percent of CMW entries supplied the Admiralty with chronometers falling slightly to 27 percent in the post Board of Longitude era.

To generate data on Board of Longitude awards for chronometer innovation, we matched the names in CMW to individuals who received a progress payment using the list of financial disbursements contained in Howse (1998). Although the longitude prize was never technically awarded, interim disbursements made by the Board can be thought of as financial progress payments, or awards,

**Table 1**  
Descriptive statistics.

	Board of Longitude 1714–1828	Post Board of Longitude 1829–1939	Full Time Period 1714–1939
Observations	271	1,065	1,336
Entry Year	1802 [23.9]	1875 [23.9]	1860 [39.6]
Exit Year	1841 [33.7]	1906 [29.1]	1893 [39.7]
Longitude Award (progress payment)	3.0%		
Prize Winner (other competitions)	6.3%	7.1%	7.0%
British Entrant	74.0%	69.7%	70.6%
Firm Entrant	36.5%	35.0%	35.3%
Maker to Admiralty	35.1%	26.9%	28.6%

*Notes:* This table shows descriptive statistics (means and standard deviations in parentheses) compiled from data in *Chronometer Makers of the World*. “Entry” and “Exit” years reflect when activity in the industry started and stopped. The descriptive statistics are for entry years between 1714 and 1828 (the Board of Longitude Era) between 1829 and 1939 (the post-Board of Longitude Era) and for the full time period 1714–1939. “Longitude Award” reflects payments for exceptional innovation made by the Board of Longitude as documented in Howse (1998). “Prize Winner” at other competitions reflect the winners of alternative prize-based awards. Entrants into the chronometer industry are distinguished by geography (“British Entrant” versus foreign) and by type (“Firm Entrant” versus an individual inventor). “Maker to Admiralty” reflects whether a chronometer inventor supplied the Admiralty, as a measure of technical excellence.



**Fig. 1.** The Location of Inventors. Notes: This figure shows the location of inventors in *Chronometer Makers of the World* in and around Europe constructed using geocoding of the specified addresses.

for exceptional innovative developments. Few inventors reached this standard of excellence. 3 percent of the CMW entries for the period 1714–1828 received a Board of Longitude award, with the largest cumulative amount being paid to Harrison.

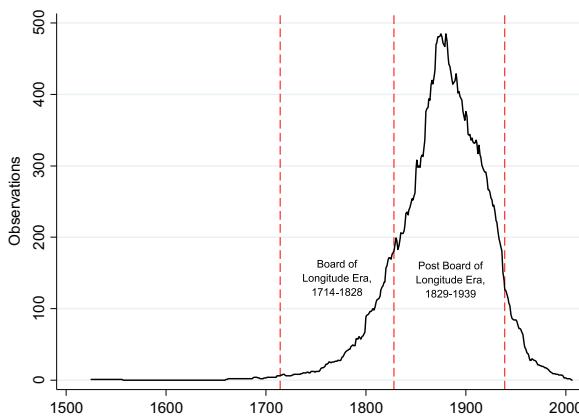
Because the Board of Longitude was not the only source of public approbation for innovation, additionally, we coded a dummy variable for whether an inventor received an award at other prize competitions. Prize competitions were commonplace during the eighteenth and nineteenth centuries, with a multitude of European, American and Asian industrial exhibitions. Mercer includes biographical details on entries which we augmented with our own literature searches. Table 1 shows 6–7 percent of CMW cohorts received a prize for chronometer innovation. For example, Jean Adrien Philippe (1815–1894), a French horologist who co-founded Patek Philippe & Co., received a gold medal at the 1844 French Industrial Exposition.

Finally, we identified patent usage by hand matching CMW names to a comprehensive dataset of British patents described in Brunt et al. (2012), including those granted in Scotland, which had its own separate registration system for patents prior to 1853.<sup>9</sup> We matched by the title of the invention to determine a chronometer-specific technology, and by name in order to obtain correspondence between the invention and inventor. Because the cost of obtaining a patent was high (by the middle of the nineteenth century a patent could cost £120 in England and as much as £350 in Scotland and Ireland) liquidity constrained inventors had the option to patent through a sponsor or an agent, who would sometimes have their own name on the patent. For example, Thomas Earnshaw (1749–1829) could not afford to patent given that fees were so high.<sup>10</sup> He received financial assistance from a watchmaker, Thomas Wright, who used his own name to patent Earnshaw's escapement invention (Sobel, 1996, p. 160).<sup>11</sup> Although we made every effort to correct for such instances, this practice (when undetected) will lead to a downward biased estimate of the propensity to patent.

<sup>9</sup> Ireland also had its own separate registration system prior to 1853, but most of the records no longer survive.

<sup>10</sup> Even by the middle of the nineteenth century patent fees were about four times larger than per capita income (Khan, 2005, p. 31).

<sup>11</sup> An escapement stalls or creates mechanical movement in a chronometer according to a set rhythm.



**Fig. 2.** The number of active chronometer makers and craftsmen. Notes: This figure plots the number of active chronometer makers and craftsmen in *Chronometer Makers of the World* over time. Entry year reflects the year when activity in the industry started.

### 3.1. The distribution of entry, exit and patents

Figs. 2 and 3 show the distribution of entry and exit for the observations contained in CMW over time. Prior to the longitude prize being established very few inventors were engaged in this area of technological development. For example, Christiaan Huygens (1629–1695), a famous Dutch scientist, mathematician and horologist built a marine chronometer in 1660 which used a pendulum and a coiled spring to moderate mechanical movement. This timepiece, however, proved to be erratic in anything but calm seas. During trials on Dutch vessels it was unable to correct for measurement errors caused by temperature variations and gravity changes at different latitudes. Still, Huygens attempted to patent his discoveries (Gould, 2013, pp. 27–30).

A key requirement of a prize competition is that it stimulates competitive entry (Kalil, 2006). Qualitative accounts indicate that the longitude prize encouraged entry and competition as the most prominent horologists were incentivized to discover a solution to the navigational problem (Betts, 1996). Yet, even after the Longitude Act was passed entry into the industry was quite protracted. Figs. 2 and 3 show a peak in activity more than a century and a half after 1714. Typically entry, exit and industry “shakeout” occurs over a much shorter interval of a few decades as technological uncertainty gets resolved.<sup>12</sup> One explanation for the different dynamics observed is the high degree of technological complexity associated with watch making. Chronometers consisted of many complex parts including a movement drawn by a weight, or spring, and an escapement. Although Harrison's dominant design was perfected by the 1770s, it took decades of incremental advance before it could be considered commercially viable.

By the same token Fig. 4 illustrates that most of the patents in the chronometer industry were granted after the Board of Longitude era. In aggregate, a small number of chronometer patents (an average of 0.13 per year) were granted between 1714 and 1828, but the use of patents increased substantially to an average of 2.30 patents per year in the period from the Board's dissolution in 1828–1939. However, when we scale the number of patents by the number of active inventors in CMW there is some evidence to suggest that the use of patents was quite high during the Board of Longitude era. Towards the end of the time period both the number of patents granted to inventors and the number of patents per inventor declined sharply. This is consistent with the fact that the industry facing a technology shock away from navigation using chronometers and towards identifying location based on radio time signals.

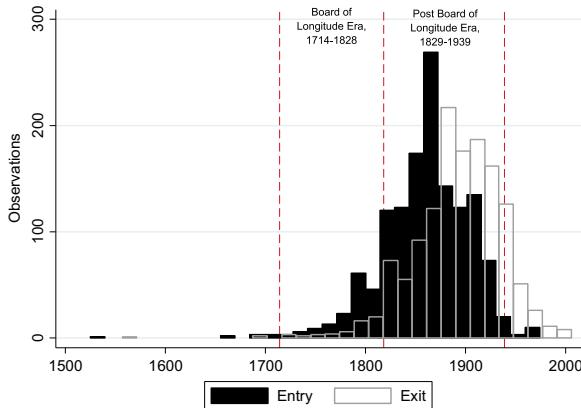
### 4. The effect of board of longitude progress payments

An important question is the extent to which inventors responded to changing incentives used by the Board of Longitude. While much of the literature on the search for longitude focuses on the main prize as a mechanism to spur innovation, a relatively neglected area is the Board's use of progress payments for successful interim developments. Fig. 5 illustrates the time series of data. We show cumulative financial amounts paid out in aggregate and we also use descriptions of payments to distinguish between awards made for “mechanical” (e.g., chronometer-based) and “celestial” (e.g., lunar-based) solutions. While it is often argued that the Board of Longitude was against mechanical solutions, such as those produced by Harrison, it is clear from the data that by around the 1770s it was heavily vested in this area of development.

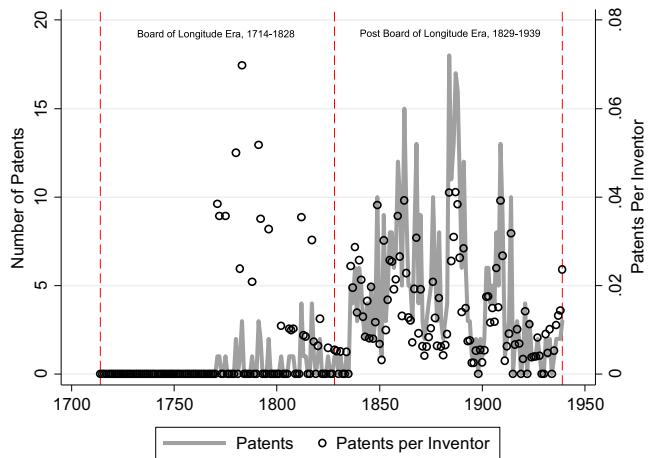
Howse (1998, pp. 407–408) documents that Harrison received a total of £22,000 from the Board of Longitude: one payment of £250 in 1737, six payments of £500 each between 1741 and 1760, £1500 in 1762, £1000 in 1764, £7500 in 1765 and a final payment of £8750 in 1773.<sup>13</sup> These were large amounts relative to the average wage and the financial cost of innovating. An engineer would have earned an average nominal wage of £138 in 1755 and £170 in 1781 (Lindert and Williamson, 1983, p. 4). Although data

<sup>12</sup> See for example comparisons like U.S. automobiles or tires, where similar data are available. In tire manufacturing, for example, Klepper and Simons (2000) document that a peak in the distribution was reached in 1922 by which time 274 firms had entered. At this point the industry was only about 25 years old.

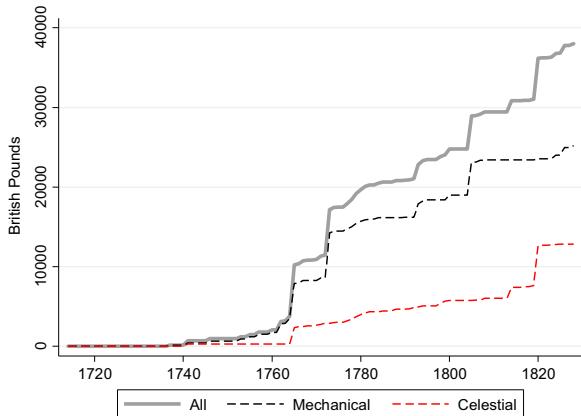
<sup>13</sup> There is some disagreement over the precise amount. While Howse (1998, pp. 407–408) documents £22,000, Gould (2013, p. 67) documents £23,050.



**Fig. 3.** The distribution of entry and exit. Notes: This figure plots the distribution of entry and exit for the number of active chronometer makers and craftsmen in *Chronometer Makers of the World* over time. Entry and exit years reflect when activity in the industry started and stopped.



**Fig. 4.** Chronometer patents 1714–1939. Notes: This figure plots the time series of chronometer patents and chronometer patents per inventor. The number of inventors active in a particular year is defined by the entry and exit years from *Chronometer Makers of the World*.



**Fig. 5.** Cumulative board of longitude award payments. Notes: This figure shows cumulative award amounts as reflected by progress payments made by the Board of Longitude for exceptional innovation. These were then categorized into mechanical (i.e., chronometer-based) and celestial awards (e.g., lunar methods) and then converted to constant 1800 values using the retail price index of Officer and Williamson (2014).

on the cost of developing an invention are limited, Allen (2009, p. 919) reports that Hargreaves's 1764 spinning jenny in the textile industry cost about £500 to develop and Arkwright's water frame about £13,000 to develop by 1774.

According to MacLeod (1988, p. 193) Board of Longitude progress payments provided a crucial function because “without the grants made him by the Board... it is most unlikely that Harrison could have perfected his chronometer.” Moreover, the influence of

these awards was not confined to Harrison. For example the Board awarded the horologist Thomas Mudge (1715–1794) £500 in 1777 for further experiments associated with precision watchmaking.

Two potential mechanisms can link these payments to innovation. First, it seems likely that the progress payments provided capital for research and development. This would have been especially important in an era where financing constraints for technological development were often binding (MacLeod et al. 2003). Second, another potential mechanism for the effect of these payments on innovation is that by both screening for ideas and providing capital to key inventors for improvement, the Board lowered the cost of experimentation for inventors like Harrison. A growing literature emphasizes that this kind of dynamic can lead to the production of more radical ideas because inventors are unconstrained to make riskier technology choices (e.g., Kerr et al. 2014). It could be argued, therefore, that the Board acted as an important intermediary, by both screening for the most promising solutions to the longitude problem and supplying capital resources for creative innovation.

Beyond these types of important effects it is also plausible that the Board shifted the direction of innovation by signaling favorable areas of development to potential innovators. Progress payments were publicly announced and Board of Longitude meetings were widely documented. The *London Chronicle* noted that a 1762 meeting was attended by a “great number of persons of distinction; and persons skilled in navigation were present.”<sup>14</sup> If progress payments for successful intermediate developments had a broad effect by changing the information set available to inventors, we would expect to observe a link with both entry and patents.

However, Fig. 6 indicates that progress payments made each year do not appear to be closely related to the number of entrants each year. This pattern in the data is also exhibited when we plot only mechanical awards against entrants. We would expect mechanical awards to be the better predictor of entry because these payments would have specifically influenced chronometer inventors. Similarly in Fig. 7 we find an absence of a close relationship between progress payments made each year and the number of chronometer patents granted each year.

We do not find a better fit between these series in a regression framework. We use variants of the following specification where  $t$  indexes time and  $AWARD$  is the monetary amount of the progress payment. We allow awards to influence our outcome measures (entrants or patents each year) with a one period lag and we log-transform the variables due to skewness in the data.<sup>15</sup> We also use a one period lag of the outcome variable as an additional control, to mitigate omitted variable bias under the assumption that unobserved factors that would influence entry will be correlated with the prior year outcome.

$$\log(OUTCOME)_t = \alpha_1 \log(AWARD)_{t-1} + \alpha_2 \log(OUTCOME)_{t-1} + \varepsilon_t$$

**Table 2** reports OLS regression results where we use the logarithm of progress payments to predict the logarithm of entry. Although column 1 of Panel A shows a statistically significant elasticity of entry with respect to aggregate progress payments, the effect is smaller and statistically insignificant in column 2. Moreover, when we disaggregate into mechanical and celestial awards, the coefficients in columns 3–6 produce counter intuitive results. Mechanical awards do not predict entry into the chronometer industry with any precision, but the celestial awards do. When conditioning on both progress payment types in the same specification in column 7 and controlling for lagged entry in column 8, this finding remains. In column 9 we restrict the entry count per year to only inventors domiciled in Britain and include macro time series covariates for British real GDP and population from Broadberry et al. (2015). In this specification we do not find any strong effect of either type of award on entry.

Equally, we do not find any substantive effect of the progress payments on patents. In **Table 2**, Panel B we find that the effect of progress payments on patents is statistically significant in columns 1 and 2 and also in column 4 when using only mechanical awards as a predictor. However, the elasticity is small in magnitude, implying a doubling in progress payments would lead to only a 2.3 percent increase in patents. In column 5 we estimate a similar elasticity with respect to celestial awards. In columns 7 and 8 the coefficients on the progress payment variables are all imprecisely estimated. In column 9 when restricting to only CMW entries domiciled in Britain and controlling for macro time series covariates we find that progress payments are not a good predictor of patents.

In sum, we do not find any quantitative evidence to suggest that by signaling developments in chronometer technology through progress payments that the Board influenced either the time series of entry or patents. Qualitative evidence suggests a more plausible mechanism through which these payments had an impact on innovation was by providing capital for promising research and development efforts to inventors who had already entered the industry.

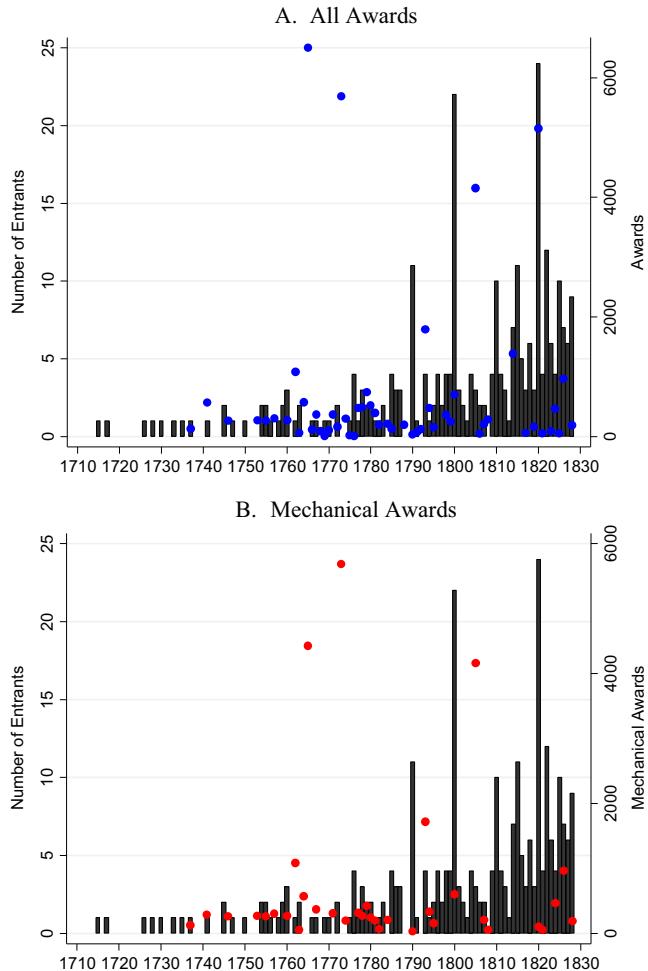
## 5. The propensity to patent

Next, we turn to the analysis of patenting at the inventor-level for the Board of Longitude and the post-Board eras. Based on our patent-matching data we report statistics for the propensity to patent in **Table 3** measured by the share of CMW entries we observe in the patent records. We find that 15.9 percent of inventors patented chronometer technologies during the Board of Longitude era rising to 18.1 percent in the post-Board era. If we exclude all foreign inventors, these shares are 18.9 percent and 20.3 percent respectively.

We benchmark these shares using existing studies. The shares we observe are much larger than the 9.6 percent patenting rate identified for all scientific instrument inventions exhibited at the Crystal Palace Exhibition in 1851 (Moser, 2012, p. 55), a category

<sup>14</sup> London Chronicle August 17, 1762–August 19, 1762; Issue 882.

<sup>15</sup> Both entry and patents are non-negative counts and there are some zeroes in the data. An alternative would be to estimate using count data models. We obtained substantively similar results using a negative binomial specification.



**Fig. 6.** The relationship between longitude awards and entry. Notes: This figure shows the relationship between entry and award amounts made by the Board of Longitude. Solid blue circles reflect all awards and solid red circles reflect mechanical (i.e., chronometer-based) awards. Bars indicate an annual count of entry compiled using the data from *Chronometer Makers of the World*. Award amounts are converted to constant 1800 values using the retail price index of Officer and Williamson (2014). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

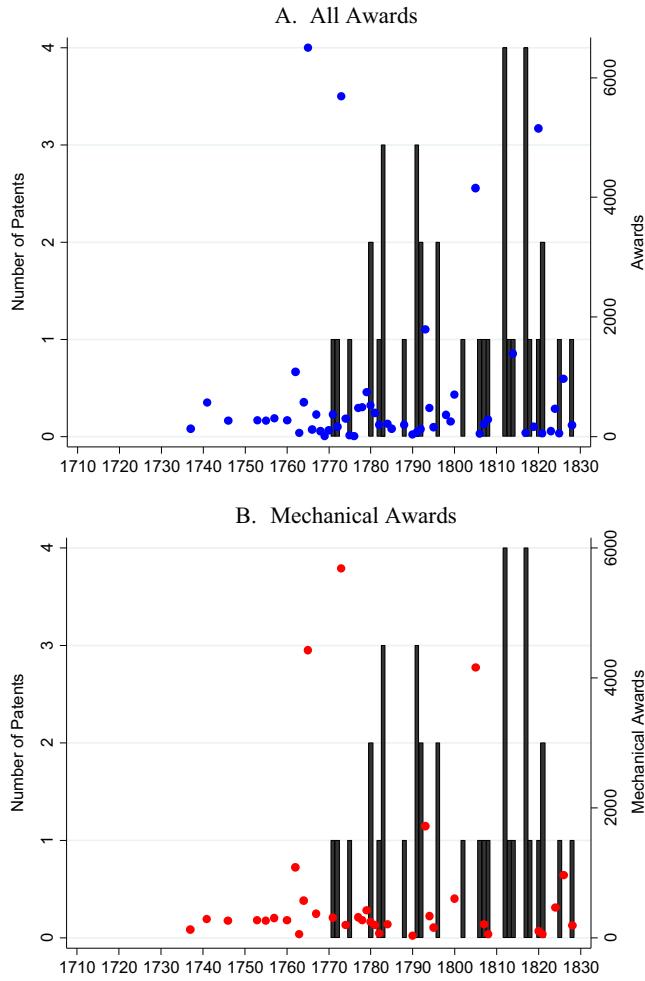
that would include chronometers.<sup>16</sup> Brunt et al. (2012) provide another benchmark. They analyze patenting at prize competitions organized by the Royal Agricultural Society of England (RASE) between 1839 and 1939. Although the shares we find for chronometers accord with theirs for all entrants, it is important to note that we would expect the rate of patenting in chronometers to have been much lower. At Crystal Palace the share of agricultural machinery exhibits patented was double that of scientific instruments (19.9 percent versus 9.6 percent respectively).

Additionally, Table 3 shows that 62.5 percent of inventors who received a Board of Longitude award patented. This suggests the most prominent inventors producing the highest quality inventions sought formal protection. While less prominent inventors may also have attempted to use patents but had their applications rejected (which is unobservable to us), comparisons across prize competitions imply a disproportionate use of the patent system by Board of Longitude award winners. Their patenting rate is four times larger than for scientific instrument award winning inventions at Crystal Palace and more than double that for award winners at RASE prize competitions. Fig. 8 shows that around two-thirds of recipients of Board disbursements patented contemporaneously to their award. This implies a close relationship between prize and patent-based incentives.

### 5.1. The propensity to patent: probit specifications

To examine the variables associated with patenting at the inventor-level we use probit regressions. In the specification below the dependent variable is coded 1 if inventor  $i$  patented and 0 if not. We measure awards using the logarithm of monetary values

<sup>16</sup> Note we measure the propensity to patent at the inventor-level (i.e., the share of CMW entrants who patented chronometer technologies) whereas the benchmark for Crystal Palace is measured at the technology-level (i.e., the share of exhibits patented). However, since most entrants in the Crystal Palace data are associated with a single exhibit, this measure should provide a reasonable approximation of the inventor-level propensity.



**Fig. 7.** The relationship between longitude awards and patents. *Notes:* This figure shows the relationship between chronometer patents and award amounts made by the Board of Longitude. Solid blue circles reflect all awards and solid red circles reflect mechanical (i.e., chronometer-based) awards. Bars indicate an annual count of chronometer patents. Award amounts are converted to constant 1800 values using the retail price index of [Officer and Williamson \(2014\)](#). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

received and an indicator coded 1 for an award and 0 otherwise. *PRIZE* is an indicator for awards received in other prize competitions, which provides us with a benchmark for comparing the propensity to patent for longitude award winners. *BL* is coded 1 for inventors entering the chronometer industry in the post-Board of Longitude era (i.e., after 1828) to control for any changes in the propensity to patent by specific cohorts of inventors. We use a vector of control indicators (*X*) to identify the geography of inventors (Britain is coded 1), firms versus individual inventors (firms are coded 1) and if an inventor was a “Maker to the Admiralty” (coded 1).

$$\Pr(\text{Patent} = 1) = \beta_1 \log(\text{AWARD})i + \beta_2 \text{PRIZE}i + \beta_3 \text{BL}i + X'i\delta + \epsilon_i$$

In Table 4 we present marginal probability effects evaluated at the mean of the continuous independent variables or for a discrete change with respect to the indicator variables. We find that the use of patents by chronometer inventors during the Board of Longitude era was increasing in the monetary value awarded. Award amounts are specified in logarithms so the estimates in column 1 show that a doubling in the award value is associated with an increase in the probability of patenting of 4.7 percent. The economic magnitude of this estimate remains approximately the same when controlling for other covariates in column 4. In terms of discrete changes, column 2 shows that winning an award is associated with an increase in the probability of patenting of 49 percent, which is robust to including controls in column 5.

Further to the discussion of the propensity to patent in Table 3 the longitude award effect on patenting in columns 2 and 4 is much larger than the effect for winning a prize at a different competition in columns 3 and 5. In fact, it is about 4 times larger in column 7 when the effects are jointly estimated.<sup>17</sup> In other words, we find a relatively stronger tendency among those who were

<sup>17</sup> In column 7 the longitude award coefficient is statistically larger than the prize coefficient under a Wald test ( $\chi^2=4.08$ ,  $p=0.044$ ).

**Table 2**

The effect of longitude awards on entry and patents.

A. Entry	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
log(Longitude Award) <sub>t-1</sub>	0.061** [0.025]	0.034 [0.021]							
log(Longitude Award) <sub>t-1</sub> (Mechanical)		0.012 [0.025]	0.001 [0.022]			-0.009 [0.029]	-0.011 [0.025]	-0.060 [0.077]	
log(Longitude Award) <sub>t-1</sub> (Celestial)				0.092*** [0.032]	0.057* [0.029]	0.095*** [0.036]	0.060* [0.032]	0.106 [0.128]	
log(Entrants) <sub>t-1</sub>		0.491*** [0.075]		0.517*** [0.075]		0.480*** [0.077]		0.480*** [0.077]	-0.076 [0.085]
GDP <sub>t-1</sub>									-0.067 [0.046]
Population <sub>t-1</sub>									0.161* [0.083]
Observations	114	114	114	114	114	114	114	114	114
R <sup>2</sup>	0.05	0.28	0.00	0.26	0.07	0.29	0.08	0.29	0.44
B. Patents	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
log(Longitude Award) <sub>t-1</sub>	0.024* [0.012]	0.021* [0.012]							
log(Longitude Award) <sub>t-1</sub> (Mechanical)		0.021 [0.013]	0.023* [0.013]			0.015 [0.013]	0.019 [0.013]	0.014 [0.013]	
log(Longitude Award) <sub>t-1</sub> (Celestial)				0.029* [0.017]	0.021 [0.017]	0.025 [0.017]	0.014 [0.017]	0.009 [0.017]	
log(Patents) <sub>t-1</sub>		0.197** [0.097]		0.229** [0.100]		0.183* [0.097]		0.203** [0.099]	0.084 [0.120]
GDP <sub>t-1</sub>									0.004 [0.006]
Population <sub>t-1</sub>									-0.004 [0.010]
Observations	114	114	114	114	114	114	114	114	114
R <sup>2</sup>	0.03	0.07	0.02	0.07	0.03	0.06	0.04	0.08	0.18

Notes: This table shows OLS regression results to test for an effect of Board of Longitude award payments on entry and patents between 1714 and 1828. The dependent variable in Panel A is an annual count of entrants into the chronometer industry. Columns 1–8 include all entrants, while column 9 includes only entrants located in Britain. Indexes of real GDP and population in Britain are from Broadberry et al. (2015). The dependent variable in Panel B is an annual count of chronometer patents. Award amounts reflect award payments made by the Board of Longitude for exceptional innovation and are compiled from Howse (1998). These were then categorized into mechanical (i.e., chronometer-based) and celestial awards (e.g., lunar methods) and then converted to constant 1800 values using the retail price index of Officer and Williamson (2014). Award amounts are specified in logarithms with one added to rescale zero values. Robust standard errors are reported in parentheses. Significance is at the \*\*\* 1 percent \*\* 5 percent and \* 10 percent levels.

granted awards by the Board of Longitude to also obtain patents.

We do not detect any statistically or economically sizeable differences between individuals and firms in terms of patenting probabilities, but we do find that inventors designated as a “Maker to the Admiralty” were more likely to patent, possibly because they were able to extract patent-based payoffs from their inventions. During the late eighteenth and early nineteenth centuries the Admiralty’s demand for chronometers increased and it put in place an institutional framework (including using the Royal Observatory at Greenwich as a store of government-owned time pieces) to ensure the supply of marine chronometers to Navy captains (Ishibashi, 2013). Being a “Maker to the Admiralty” reflected a coveted standard of excellence.

Perhaps surprisingly, we do not find a difference in the likelihood of patenting across British and non-British inventors. We might

**Table 3**

Comparisons of the propensity to patent.

Chronometer Manufacturers of the World	Crystal Palace (1851)	RASE (1839–1939)
Patented (Entry, 1714–1828)	15.9%	Scientific Instrument Exhibits Patented
Patented (Entry, 1829–1939)	18.1%	9.6%
Longitude Award Winners who Patented	62.5%	Entrants who Patented
		17.7%
		Award Winners who Patented
		28.0%

*Notes:* This table shows the percentage of inventors in *Chronometer Makers of the World* who patented by entry cohort and for longitude award winners. The second column of percentages is taken from [Moser \(2012\)](#), p. 55 and shows the share of exhibits patented at the Crystal Palace Exhibition in 1851. We use this comparison under the assumption that the share of exhibits patented (technology-level) is an approximation of the share of exhibitors (inventor-level) who patented. The third column of percentages are calculated from the data in [Brunt et al. \(2012\)](#) and show the share of entrants and award winners who patented at *Royal Agricultural Society of England and Wales* (RASE) prize competitions held between 1839 and 1939.

expect to find a positive coefficient on the variable for inventors located in Britain, under the assumption that it was easier to manage patent filing procedures domestically than from abroad ([Khan, 2005](#)). On the other hand, patent agents could facilitate transactions from overseas. Also London was the main center of the watch making industry so it could be that foreign inventors faced added incentives to patent in Britain.

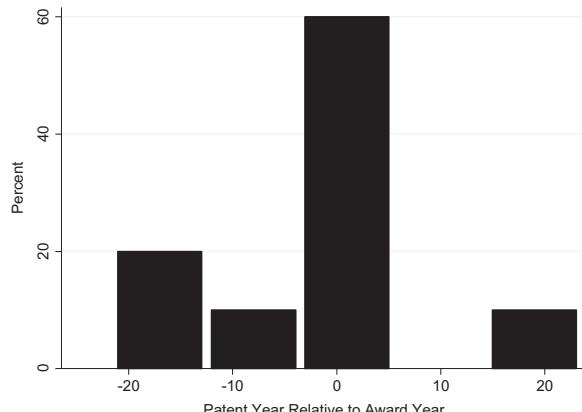
Finally, in line with the descriptive statistics in [Table 3](#), we find some evidence of a change in the probability of patenting conditional on entry cohort. The coefficient on the indicator variable identifying the post-Board of Longitude era is positive and statistically significant in four of the seven specifications in columns 1 to 7, although we do not find any evidence of interactive effects in column 8. We would expect the main effect of the propensity to patent to increase over time, because of legal changes such as the 1852 and 1883 Patent Acts which reduced the cost of accessing intellectual property rights ([Nicholas, 2011; Kuegler, 2016](#)).

### 5.2. A complementary relationship between prizes and patents

Why did inventors tend to patent rather than keep their inventions secret, especially the most significant inventions associated with Board of Longitude awards? Theoretical perspectives suggest the decision could have gone either way. According to [Anton and Yao \(2004\)](#) inventors should only patent minor inventions, keeping the most important inventions secret to avoid costly disclosure. On the other hand, [Kultti et al. \(2007\)](#) show that if inventors engage in simultaneous invention and the risk that someone else will patent is high, patenting dominates over secrecy. Under these circumstances the patent system creates welfare benefits because disclosures associated with patents leads to the spread of information across innovators.

One explanation for the high rate of patenting we observe is that intellectual property rights afforded inventors protections that the longitude prize could not. Whereas the Board required lengthy due diligence to establish if a chronometer had satisfied the standards for winning the longitude prize, the protection of patenting was more immediate. As [Bottomley \(2014\)](#) argues, “inventors were able to obtain and enforce patent rights with relative ease” at this time. Furthermore, being recognized by the Board of Longitude for exceptional innovation was a powerful form of advertising ([Ishibashi, 2013](#)), which could augment payoffs from a proprietary invention. If patents and prizes offered complementary benefits, it made sense to utilize both.

Permitting inventors to patent may have also had complementary attributes from a policy standpoint for at least two reasons. First, the patent race literature emphasizes that while the race to patent may lead to the inefficient duplication of effort, more investment leads to faster innovation ([Loury, 1979](#)). To the extent that the search for longitude was one of the most pressing technological challenges of the eighteenth century, the high social returns associated with a solution would have arguably justified the cost of duplicate investment. Three inventors are distinguishable for their overlapping technological discoveries. All patented and received Board of Longitude awards. Thomas Mudge patented the “lever” escapement in 1766 and was awarded £3000 by the Board



**Fig. 8.** The timing of patents and longitude awards. *Notes:* This figure shows the timing of patents relative to the year a progress payment was made by the Board of Longitude to an inventor. Negative values on the x-axis indicate patenting prior to an award and positive values reflect post-award patenting.

**Table 4**

The inventor-level determinants of patenting.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
log (Longitude Award) (£ amount)	0.047** [0.020]			0.046** [0.019]				
Longitude Award (indicator)		0.488*** [0.166]			0.484*** [0.166]		0.493*** [0.164]	
Prize Winner (other competitions)			0.141*** [0.050]			0.118** [0.049]	0.121** [0.049]	0.021 [0.109]
British Entrant				-0.013 [0.028]	-0.013 [0.028]	0.000 [0.028]	-0.004 [0.028]	0.066 [0.059]
Firm Entrant				0.020 [0.025]	0.019 [0.025]	0.014 [0.025]	0.017 [0.025]	0.050 [0.057]
Maker to the Admiralty				0.095*** [0.030]	0.095*** [0.030]	0.083*** [0.030]	0.081*** [0.030]	0.043 [0.062]
Post-Board Era (BL)	0.044 [0.027]	0.046* [0.027]	0.027 [0.027]	0.051* [0.027]	0.052** [0.027]	0.035 [0.027]	0.050* [0.027]	0.084 [0.052]
BL×Prize Winner								0.113 [0.141]
BL×British Entrant								-0.085 [0.074]
BL×Firm Entrant								-0.039 [0.058]
BL×Maker to the Admiralty								0.044 [0.072]
Observations	1,163	1,163	1,163	1,163	1,163	1,163	1,163	1,163
Log pseudolikelihood	-564.25	-563.44	-562.99	-557.60	-556.81	-557.64	-553.26	-556.11

*Notes:* This table shows probit regression results to explore the inventor-level determinants of patenting. Coefficients are marginal effects evaluated at the mean of the continuous variables and for a discrete change in indicator variables. The dependent variable is an indicator coded 1 for patent usage and 0 otherwise. Award amounts are specified in logarithms with one added to rescale zero values. “Post-Board Era” is an indicator for entry between 1829 and 1939. The full dataset includes 1,336 observations, but data are missing for some of the variables included. Hence, we use 1163 observations for which we have complete data across the specifications. Robust standard errors are reported in parentheses. Significance is at the \*\*\* 1 percent \*\* 5 percent and \* 10 percent levels.

for design ingenuity and workmanship. Thomas Earnshaw patented his “spring detent” escapement in 1783, while John Arnold (1736–1799) had patented a variant of this technology in 1782 (Betts, 1996). Despite intense debate over who was the first inventor, both Earnshaw and Arnold were awarded £3,000 by the Board in 1805, the joint highest amount for a mechanical solution, along with the sum paid out to Mudge.<sup>18</sup>

Second, the Board was concerned with incentivizing inventors, while also ensuring that knowledge was diffused. Allowing inventors to patent had benefits in terms of opening technical ideas up to the public. As John Harrison opted for secrecy to protect his ideas, the Board was forced to take additional measures to promote disclosure. Following a partially successful trial of Harrison’s H4 to Jamaica and back in 1761–1762, a 1763 Act was passed to encourage Harrison to reveal information to make his chronometers fully replicable by British watchmakers.<sup>19</sup> Because placing this information in the public domain would disadvantage Harrison, the Act stipulated that no other person could win the prize within a four year period. Although the Board modified its approach to prize-based incentives over time, it seems to have consistently recognized that inventors would seek to patent. Notably, in 1782 the Board declined an offer made by John Arnold to “buy-out” his patents. By patenting, Arnold had already disclosed some of the key principles in the design and construction of his inventions (Gould, 2013, pp. 113–114).

<sup>18</sup> John Roger Arnold received the award since his father died in 1799.

<sup>19</sup> The 1763 Act was titled: “An Act for the Encouragement of John Harrison, to publish and make known his Invention of a Machine or Watch, for the Discovery of the Longitude at Sea.”

## 6. Post-1714 prizes for chronometers

The final component of our analysis examines patents over the life cycle of the chronometer industry in the context of the changing role of prize and patent-based incentives. In 1774 John Harrison successfully petitioned Parliament and received a final monetary award of £8750 to supplement the amounts he had already received from the Board of Longitude, but this did not indicate that the longitude problem had been solved. In fact, the same year a new schedule of awards was established under an Act of Parliament. A prize of £5,000 was set for a method that could determine longitude within one degree, £7500 for within two-thirds of one degree and £10,000 for within half a degree.<sup>20</sup> That is, the new legislation maintained the same location parameters as the 1714 Act, but prize levels were set at half the original amounts.

Perhaps more importantly, in 1818 as part of a radical reorganization of the Board of Longitude, these prize amounts and award conditions were revised again and the position of a Superintendent of Chronometers was created with the responsibility for administering formal chronometer trials at the Royal Observatory in Greenwich. The Board had initially sent Harrison's chronometers there to be subjected to scientific scrutiny, and from 1823 to 1835 the Admiralty continued this effort by instigated a series of "premium trials" to encourage inventors to develop chronometers for more accurate time-keeping.

Monetary prizes were awarded at these trials for first, second and third place and entries were scientifically evaluated. A formula ( $a+2b$ ) was used to measure a chronometer's accuracy. Daily measurements were taken against a synchronized clock with  $a$  being the difference in seconds between the greatest and the least weekly sums of the daily rates and  $b$  being the greatest difference between two consecutive weekly sums of the daily rate rates. The metric was scientifically and practically oriented:  $a$  would reflect week-to-week precision, a key factor on short voyages, and  $b$  would reflect long-term precision, a key factor on distant voyages. The smaller the value of  $a+2b$  the more accurate the chronometer was considered to be.

As in the original longitude prize, inventors entering for competition and winning awards were not barred from patenting. In an attempt to promote the diffusion of knowledge, the Admiralty published detailed accounts of technical ideas. A chronometer developed by a respected London-based maker Robert Molyneux (d. 1876), who had worked under Thomas Earnshaw, was awarded a £200 prize at the premium trials in 1832 ( $a+2b=12.3$  comprising of 6.7 for  $a$  and 2.8 for  $b$ ).<sup>21</sup> Molyneux also patented. In 1842 an *Account of Improvements in Chronometers* was published by the Admiralty, including Molyneux's patent specification.

We find a link between these prize competitions and patents using simple difference-in-differences regressions. We compare changes in chronometer patents (the treatment group) against a control group of scientific instrument patents. We assume that patenting in the control group would be affected by the same potentially endogenous influences as the treatment group, such as changes in demand conditions or scientific opportunities. In the absence of an official concordance of individual patents to technology categories, we followed the procedure outlined in Brunt et al. (2012) and used keywords to identify these inventions from patent titles.<sup>22</sup>

In the specification below  $j$  indexes technology categories and  $t$  indexes time. Given that we observe a small number and sometimes zero yearly patents in the data (see Fig. 4), we collapsed the observations into a dataset of decade-level means. We then took the logarithm of this variable adding one to rescale zero values.  $CHR$  is an indicator coded 1 for chronometer patents and 0 for patents in the control category and  $TD$  represents time period decade dummies. Technology area fixed effects  $\phi_j$  capture any systematic time-invariant differences in patenting across technology areas. Time fixed effects  $\gamma_t$  control for common unobservable shocks such as variation in the cost of patenting.

$$\log(PATENTS)_{jt} = \delta_1 CHR_j \times TD_t + \varphi_j + \gamma_t + e_{jt}$$

**Fig. 9A** plots OLS point estimates and 95 percent confidence intervals for  $\delta_1$  from the 1800s to the 1930s relative to a baseline from the 1710s to the 1790s. In **Fig. 9B** we provide comparable results to the log-linear model using a negative binomial estimator, a common approach in the patent literature given the distributional characteristics of patent data, which typically contain a non-trivial number of zeros. We use both leads and lags around the premium trial period. The coefficients for the 1800s and the 1810s serve as tests for pre-treatment effects and the estimates do not suggest any strong anticipatory change in the level of chronometer patents compared to the change in the level of scientific instrument patents.

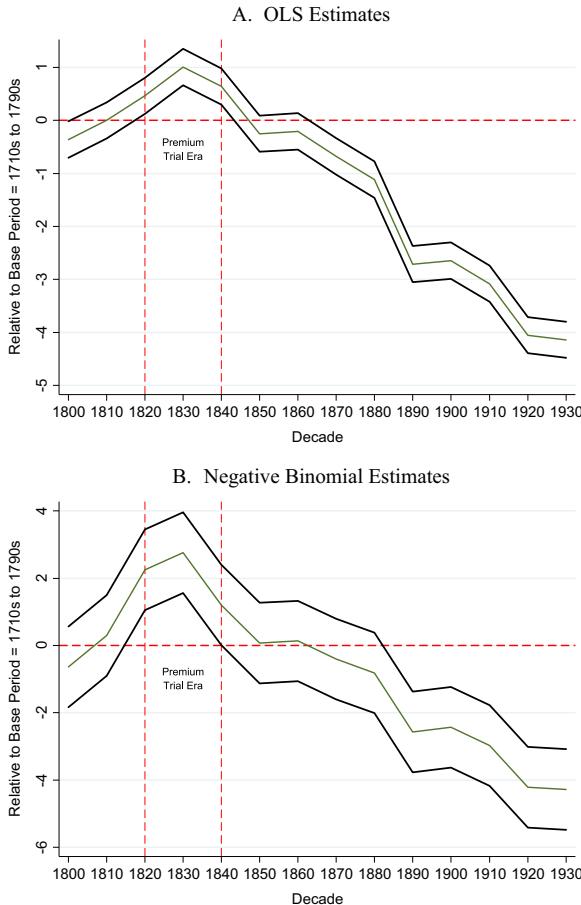
The spike in patenting during the time period associated with the premium trials from 1823 to 1835 is clearly evident both in the OLS and negative binomial results. In terms of economic magnitudes the OLS results imply a 59 percent relative increase in the mean number of chronometer patents during the 1820s and a 174 percent relative increase during the 1830s. Although we cannot rule out that the premium trials were held at a time when opportunities for scientific advancement in chronometers were high, this evidence is consistent with findings we have presented throughout the paper linking prizes and patents.

Finally, note that the coefficients become strongly negative towards the end of the time period and the drop in chronometer patents compared to scientific instrument patents is quite dramatic. This makes sense from the standpoint that payoffs would be less

<sup>20</sup> The new Act also stipulated that if longitude was determined within given tolerances using solar and lunar methods, the prize award would be £5000. It also shifted the emphasis from longitude to navigation more generally.

<sup>21</sup> Measurement occurred over 29 weeks under variable simulated conditions. See Gould (2013, pp. 257, 267–272).

<sup>22</sup> We derived list keywords from publications such as Gerard L'Estrange Turner's, *Scientific Instruments 1500–1900*. These are: accelerometer, ammeter, amperage, anemometer, armillary, astrolabe, barometer, caliper, calorimeter, catheter, chartometer, circumferentor, clinometer, dental, dipleidoscope, dynamometer, eidograph, electrometer, electroscope, ellipsometer, graphometer, gravimeter, hodometer, hygrometer, inclinometer, interferometer, kaleidoscope, lithotomy, magnetograph, magnetometer, manometer, micrometer, microscope, nocturnal, ohmmeter, opisometer, optical, oscilloscope, pantograph, pedometer, planetarium, planimeter, reflector, refractor, sand glass, scale, seismometer, sextant, spectrogram, spectrometer, stereoscope, sundial, telescope, theodolite, thermocouple, thermometer, voltmeter, zograscope.



**Fig. 9.** Chronometer patents relative to scientific instrument patents around the time of the premium trials. Notes: These figures show coefficients and 95 percent confidence intervals derived from OLS and negative binomial difference-in-differences specifications to compare the change in chronometer patents (the treatment group) to the change in scientific instrument patents (the control group) around the time of the Admiralty's premium trials for chronometer innovation held at Greenwich, London during the 1820s and 1830s.

likely to accrue to invention because by the middle of the nineteenth century the longitude prize was obviated and the industry had reached a more mature stage of the product life cycle. While Harrison's chronometer cost £450 to construct in 1769, by 1840 a chronometer could be produced for as little as £40. As one authority stated in 1842, "the chronometer may now be considered as an instrument of comparatively general manufacture. It is no longer dependent upon government patronage" (Davies, 2006, p. 515).

## 7. Conclusion

The longitude prize is the definitive example of a government-sponsored attempt to promote innovation. Yet, due to a lack of data and empirics, major gaps still exist in our understanding of how the longitude prize functioned. We have attempted to provide a wide-ranging analysis using new data on marine chronometers inventors over the life cycle of the industry.

Our results suggest that the longitude problem was solved due to a complementary relationship between prizes and patents. We have argued that the 1714 prize led to entry and intense competition by skilled inventors, and progress payments provided by the Board of Longitude financed interim research investment. At the same time, the propensity to patent was high. While inventors could potentially use the advertising benefits of prizes to extract payoffs during the patent term, from a policy perspective disclosure requirements through patents created opportunities for the spread of knowledge across innovators. During both the Board of Longitude and premium trial eras, the government did not insist on a transfer of patent rights, nor did it "buyout" patents by influential inventions.

We cannot address the counterfactual trajectory of innovation had the 1714 prize been designed at the outset with more stringent requirements for disclosure. Under those circumstances the prize may have been an effective substitute for patenting. However, with a disclosure requirement John Harrison may not have entered, and without patents the cost of inventing may have been too high. Although our analysis cannot speak to these central issues, we have shown how the marine chronometer was developed in an environment characterized by the intersection of prize and patent-based incentives. We view this as an important undertaking because of the significance of the marine chronometer in the history of science and technology, and the recurrent policy debate

concerning the types of mechanisms that are most conducive to promoting innovation.

## Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at <http://dx.doi.org/10.1016/j.eeh.2016.09.001>.

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