THE
ECONOMIC
JOURNAL

The Economic Journal, **125** (*December*), 2052–2076. Doi: 10.1111/ecoj.12166 © 2014 Royal Economic Society. Published by John Wiley & Sons, 9600 Garsington Road, Oxford OX4 2DQ, UK and 350 Main Street, Malden, MA 02148, USA.

THE PRODUCTIVITY OF WORKING HOURS*

John Pencavel

Observations on munition workers, most of them women, are organised to examine the relationship between their output and their working hours. The relationship is non-linear: below an hour's threshold, output is proportional to hours; above a threshold, output rises at a decreasing rate as hours increase. Implications of this finding for the estimation of labour supply functions are considered. The findings also link up with the current research on the effects of long working hours on accidents and injuries.

In empirical research on measuring the input of labour in production, hours of work are treated in different ways. One approach is to neglect work hours entirely and to measure the input of labour by the number of employed workers. Another practice is to use worker-hours, the product of the number of workers and average hours per worker, implying that a given proportionate change in the number of workers has the same effect on the labour input as the same proportionate change in working hours per worker. Either of these procedures might be correct although it would seem worthwhile to ascertain whether it is. As it is, in each recession, calls are made to alleviate unemployment by reducing work hours among the employed. After all, if the labour input is simply the sum total of hours worked by all workers, so the reasoning goes, this sum can be arrived at if each works fewer hours and more people are employed.

Another research tradition recognises that changes in working hours do not entail the same changes in effective labour input because individuals tend to work with greater efficacy at shorter hours. Economists engaged in growth accounting research posit that workers employed for fewer hours were more productive during these hours so that gains in output per hour offset, in part, a shorter working week. Thus Denison (1962) suggested that, at the level of working hours in 1929 (when the average working week was 49 hours), a reduction in hours would be fully offset in gains that would leave output unchanged. At the hours prevailing in 1957 (when hours averaged 40), Denison surmised that a 10% cut in hours would result in a 6% reduction in output.[1]

Denison's conjectures build on a long history of case studies in which a few employers have investigated the consequences of cuts in their employees' working hours. A well known case was that at the Salford Ironworks in 1893 where William Mather cut his employees' weekly hours from 53 to 48.[2] Mather deemed it a success as

* Corresponding author: John Pencavel, Department of Economics, Stanford University, Stanford, CA 94305-6072, USA. Email: pencavel@stanford.edu.

Research assistance from Shirlee Lichtman is gratefully acknowledged. Conversations with David Card, Avner Greif and Priya Satia during the preparation of this article were helpful as were three referees' comments on an earlier draft. The data used in this article are available in an online Appendix which also contains graphs on output and hours and tables of descriptive statistics.

[1] Similar arguments were made by Matthews *et al.* (1982).

[2] McIvor (1987, p. 728) describes how the employers' federation campaigned against other firms following Mather's initiative claiming, implausibly, that if they did it 'would result in a very large increase in the cost of production'. Goldmark (1912) describes some of these early case studies.

did some government ministers who instituted a shorter working week in state-managed enterprises including the Woolwich Arsenal. This inspired Ernst Abbé at the Zeiss Optical Works at Jena in Germany to cut the length of the workday from nine to eight hours.

Early in the twentieth century, in the US, the National Industrial Conference Board commissioned a number of studies on the effects of shorter hours. The focus of these and subsequent reviews (Kossoris and Kohler, 1947; Brown, 1965) was on ‘before’ and ‘after’ comparisons: did output fall after a discrete cut in working hours? The results in this article are based on more than two observations (‘before’ and ‘after’) on hours and suggest that the effect on output of a reduction in hours depends on the initial level of working hours.

Aggregate production functions[3] have been estimated in which the effects of variations in the number of workers are distinguished from the effects of variations in hours worked per worker. In this article, the observations on working hours are at the level of the workplace. Also, the values of hours studied below extend over a wider range than typically available. For instance, in Feldstein’s (1967) article on hours and employment in a Cobb–Douglas production function, working hours in 1960 across 24 industries ranged from 41 to 50 hours per week and the coefficient of variation in hours was 0.076. By contrast, the observations over time examined in subsection 3.1 below range from 24 to 72.5 hours per week and their coefficient of variation is 0.200.

A simple conceptual framework is to suppose that, if H_i is worker i’s hours of work over a period of time and if E_i is i’s work effort per hour over that period, then i’s effective labour input, L_i, may be defined as $L_i = E_i \times H_i$, an expression without empirical content, as yet, because E_i is unobserved. If E_i is simply a constant, a, then $L_i = a \times H_i$ and worker i’s effective labour input is proportional to his working hours and, if i is typical of workers, a firm’s effective labour input is the sum of hours worked over all workers, a justification for the use of worker-hours.

More plausibly, i’s work effort depends on his hours of work: $E_i = f(H_i)$ where $f(H_i)$ embodies the stress, fatigue, monotony and stimulation that accompanies work. In this event, the output-hours relation depends on the form of $f(H_i)$. If $f(H_i) = a_0 + a_1 \times H_i$ where $a_0 > 0$ and $a_1 < 0$, then $L_i = a_0 \times H_i + a_1 \times H_i^2$ and i’s effective labour input rises with hours worked but at a decreasing rate. If i’s effort is a positive quadratic function of hours, then his effective labour input is a cubic function of his hours which could justify Denison’s conjectures. The research below may be interpreted as an investigation into the shape of $f(H_i)$.

A shortcoming of the data studied here is the small number of observations: for scholars accustomed to research based upon thousands of data points, the research reviewed here may appear almost anecdotal. Perhaps it is. However, many of the (often unobserved to the researcher) differences among workers in contemporary data sets are smaller when examining workers in the same plant doing the same work at the same time. Also, anecdotal or not, these observations were influential in decisions to reduce working hours.

[3] The aggregation is usually at the level of industries as in Feldstein (1967), Leslie and Wise (1980), Hart and McGregor (1988), or Marti (2000). Hamermesh (1993) reviews this work.

The evidence in this article on the effect of working hours on output is drawn from the research undertaken by the investigators of the British Health of Munition Workers Committee (HMWC) during the First World War, the Great War. This Committee, charged with providing the Minister of Munitions with advice regarding the health and efficiency of workers in munition plants, commissioned studies within munition factories into the link between work hours and work performance as part of its investigations. In recent years, there have been several useful reviews of the research conducted within firms, (see Harrison and List, 2004; Bandiera *et al.*, 2011), but this literature has overlooked the earlier work done by the investigators of the HMWC and by the subsequent Industrial Fatigue and Industrial Health Research Boards. This research almost a century ago on the stressful effects of long hours of work is likely to be relevant today for certain workers as reviewed below. First, consider the context for the research conducted by the HMWC investigators.

1. The Health of Munition Workers Committee

1.1. *The Setting*

In 1914, the outbreak of war caused the government to suspend regulations on work hours in plants producing war-related material. The working week was extended and 'the employment of men for 70–90 hours a week was common, for over 90 hours was not infrequent, and there were even cases of hours in excess of 100' (see Health of Munition Workers Committee, 1919, para. 122). Sunday work was reintroduced. Even though hours had probably been reduced somewhat since the beginning of 1915, by the first half of 1916, a random survey of over 3,000 men at eight armaments factories still found more than a third of those aged 41 years and older were working 70–100 hours per week while 58% of boys aged 18 years and younger were working more than 60 hours per week. A majority of 1,326 women in munition factories were at work more than 60 hours per week.[4]

For almost two years, the military relied on volunteers[5] and called for 'men, more men, and still more men' (Herbert Kitchener) and for 'munitions, munitions, more munitions' (John French). The departure of young men to the military and the voracious demand for munitions resulted in a huge demand for workers in the munition plants. This demand was satisfied, principally, by young women working long hours. By the end of the War (December 1918), three-quarters (precisely 77.6%) of all employees in the Ammunition and Explosives industry were women.

The replacement of younger men by novice workers was not welcomed by some of the older skilled men in the munition plants. Their concern was that the work would be divided into a number of smaller operations, each of which requiring little skill, and their control over the entire work process would be undermined. Ultimately, their skilled wages would be challenged. This process was known as 'dilution'; 'deskilling' might be the word used more often today.[6]

[4] These were reported by Agnew (1917) and Campbell and Wilson (1917).

[5] The conscription (draft) of unmarried men aged 18–41 years started in March 1916 and extended to married men in May 1916. In 1918, the age limit on military service was raised to 51 years.

[6] Hart (2007) describes a similar concern just before and during the Second World War.

Given the doubts about the wisdom of long hours, the newly formed Ministry of Munitions established the HMWC in September 1915 to consider and advise on questions of industrial fatigue, hours of labour and other matters affecting the personal health and efficiency of workers in munition factories and workshops. The Committee took up many issues relating to work activity including the quality of the working environment inside factories such as the food and water available to workers, washing facilities, protective clothing, temperature, ventilation and lighting as well as injuries, accidents, diseases and prolonged standing. The HMWC paid attention to the exposure of these workers to noxious chemicals and gases contained in the shells, components that caused fatalities through poisoning and that resulted in some huge explosions. Work in munition factories was dangerous and the HMWC recommended steps to protect the workers from harmful elements.

1.2. *Output and Hours*

An important part of their investigation was directed to the arrangement and duration of work including the association between the output of workers and their hours of work, the focus of this article. The HMWC heard different views on the desirable length of work hours but they attached significance to the fact that they knew of 'no employer who had once adopted the shorter scale of hours ever desires to return to the longer period'. The value of systematic information on the link between the output of workers and their hours of work was clear. To this end, the HMWC commissioned quantitative investigations into the factors affecting the efficiency with which individuals worked in the state-regulated munition plants.

The HMWC operated for a little over two years and produced 21 Memoranda on activities in munitions plants. Because its findings and recommendations were relevant to workplaces in other industries, shortly after its disestablishment at the end of 1917, a new agency (the Industrial Fatigue Research Board) was formed in July 1918 'To consider and investigate the relations of the hours of labour and of other conditions of employment including methods of work, to the production of fatigue, having regard both to industrial efficiency and to the preservation of health among the workers' (HMWC, 1919, p. 000). From 1921, this Board became an arm of the Medical Research Council and, in recognition of its broader agenda, in 1928 it was renamed the Industrial Health Research Board.

1.3. *The Recommendations of the HMWC*

From the evidence they viewed, in January 1916, the HMWC recommended shorter working hours: for men, hours of no more than 65–67 per week (13–14 hours daily) on average and for boys, for girls and for women a maximum of 60 weekly hours. The basis for these recommendations was not because shorter hours would yield higher average product or higher marginal product but because total output would be unchanged. This remarkable claim is explored below.

In addition to endorsing the value of regular holidays and rest pauses, the Committee was critical of Sunday work. They wrote, 'The evidence is conclusive that Sunday labour by depriving the worker of his weekly rest offers him no sufficient opportunity for recovering from fatigue, and is not productive of greater output except for quite short and isolated periods .... seven days' labour only produces six days' output and .... reductions in Sunday work have not in fact involved any appreciable loss of output' (HMWC, 1916, p. 000). Thomas Loveday was quoted: 'the effects of Sunday labour are, as has now been recognised, still worse than those of overtime hours in the evening or on Saturday afternoon' (Loveday, 1917, p. 44). In its Final Report in April 1918, the HMWC modified its earlier recommendations by urging even shorter work hours: 'the length of hours of employment provisionally recommended two years ago are now too long and can be reduced without loss of output' (HMWV, 1999, p. 122).

1.4. *Night Work*

Before the War, Britain subscribed to an international convention prohibiting the employment of women on night work. This ban was lifted with the needs of war and the HMWC deemed that, given the military's demands for shells and, even though it is 'unnatural to turn night into day', night work would be inevitable for workers throughout the War.

In assessing the relative merits of day work and night work, the HMWC distinguished between continuous and discontinuous shifts. A discontinuous schedule involved alternating between one week (or fortnight) of day work followed by one week (or fortnight) of night work for a given body of workers. The continuous schedule maintains workers on night work without an interval of day work or the schedule keeps workers on day work without a period of night work. The Committee believed the continuous system of night work denied workers complete sleep and rest which are more difficult to secure during the day. The HMWC took a benign view of night work on the discontinuous system: 'there is no significant difference between the rate of output in night and day shifts managed on the discontinuous system. If there be any difference, it would seem that the output is slightly better by night for the particular class of work involved'.

2. A General Description of the Data Collected by the HMWC's Investigators

The description of the data in this Section applies to all the observations investigated below.

2.1. *Working Hours*

The investigators distinguished between scheduled hours of work and actual hours of work by subtracting from scheduled hours time 'lost' to sickness, absence, meal times, interruptions and time spent in setting up before production and cleaning up after spells of production. 'Lost time' through sickness was sometimes attributed to the fatigue following long hours of work. In the analysis below, hours of work refers to actual work hours, not to scheduled hours.

Variations in work hours arose from not only the military's demands for munitions but also from illness, temporary shortages of raw material and from shorter hours scheduled around holidays at Christmas, the New Year, Easter and Whitsun. Most of the observations are drawn from the year 1916, a year in which major military campaigns were waged involving terrific loss of life and extraordinary expenditure of shells.[7]

2.2. *Output and Earnings*

Most of the workers were paid on a piece-rate basis. Their output formed the basis of their wage payments and allowed the researchers to have a well-defined measure of performance. In some instances, the output measure is simply the number of shells produced but, in cases where the workers were engaged in a particular stage in shell production, the investigators report an index number of their output. 'The shrill, demented, choirs of wailing shells' and the women (the 'canaries') who made them were defining elements of the Great War.[8]

Precise piece-rates or hourly earnings are not provided in the investigators' commentaries but they are described as affording the workers a relatively high standard of living.[9] 'Their rates of pay varied more or less with the cost of living' (Vernon, 1940, p. 16).

2.3. *Restriction of Output*

Can observations during a national emergency when individuals were exhorted to work for collective goals be the basis of valid inferences about the workers' behaviour in 'normal' peace-time conditions? In one sense, the unusual conditions of war resulted in a more unconstrained work situation than that prevailing in peace. Before the Great War, various restrictions on work in British industry were widely noted, especially among piece-rate workers. They were inspired by the fear that workers who produce high levels of output – 'rate busters' – will cause an employer to believe the piece-rate has been set at an unnecessarily high level and the employer would cut the rate. To prevent such behaviour, workers were prevailed upon to produce below some threshold. Some restrictions on output were prompted by trade union activity but, in other cases, they were enforced by unorganised workers. Differences among workers in the extent of these restrictions would frustrate the process of drawing inferences about the relationship between output and work hours. The Munitions of War Act of 1915 prohibited all restrictions on output in munition plants.[10] The Act banned strikes and

[7] Woollacott (1994, p. 67) notes that, 'In the buildup before the launching of the Battle of the Somme, the Woman Worker complained that, despite union protests and questions in the House of Commons, the Ministry of Munitions had allowed the Vickers Factory at Erith and a national factory at Huddersfield both to change from eight-hour shifts to 12-hour ones, and Vickers at Barrow seemed about to do the same. Factory holidays were often postponed or cancelled due to the exigencies of War as decided by the Ministry of Munitions'.

[8] The British Army was said to have fired 170 million shells by the end of the War. The shells and the women appear in poems (such as Wilfred Owen's 'Anthem for Doomed Youth') and in novels referring to the 'yellow-skinned women' (Barker, 1992).

[9] 'She worked in a factory, she said, making detonators. Twelve-hour shifts, six days a week, but she liked the work, she said, and it was well paid. 'Fifty bob a week . . . I was earning ten bob before the war' ' (Barker, 1992, p. 89).

[10] In the data analysed below, the investigators state that restrictions on output were absent.

lockouts in the munition industry (with disputes resolved through compulsory arbitration), a worker was not permitted to leave a munitions employer for another without the previous employer's permission in the form of a leaving certificate,[11] and changes in wage rates required the approval of the Ministry of Munitions. Quasi-judicial tribunals enforced these provisions.[12]

These features were a radical departure from the 'night watchman' role for government that Britain aspired to in peace so there is good reason to question whether patterns of behaviour exhibited during this War offer lessons relevant to less state-regulated labour markets. The principal concern of this article – the link between the hours worked by employees and their output – may be affected by the Act's regulations and by the extra effort summoned to defeat the country's enemy although the way in which the relation is affected – if at all – is difficult to determine without recourse to more observations. One may surmise that, during a national emergency, workers might suppress fatigue that would emerge in peacetime.

2.4. *Health*

The HMWC not only commissioned research on the link between working hours and output but also authorised the study of sickness. Physical examinations of many workers were conducted. From data on sickness rates (as documented by medical certificates) collected from 'all parts of the country', Loveday (1917, p.44) identified a number of empirical regularities associated with work. He determined that work before breakfast ('an inheritance partly from the necessary habits of agriculture') was both harmful to the worker's health and relatively unproductive work time. From the sickness rates at different munitions factories, he concluded that 'the effect of long hours, much overtime and especially Sunday labour, upon health is undoubtedly most deleterious'.

This is relevant to the study of the link between working hours and output because it suggests a possible selection problem: this output-hours association will be measured in the next subsection for those workers on the job; owing to a greater incidence of sickness, those workers on relatively long work shifts are more likely to be absent from work. In other words, the output-hours relationship will be measured from observations on those workers whose work hours have not caused them to miss work because of sickness and, in this respect, the relationship estimated will be fitted to those workers with greater tolerance of long work hours. In using observations on relatively healthy workers, the impact of long hours on worker fatigue may be understated.

2.5. *Other Factors*

The HMWC investigators recognised other factors affected the output of these workers such as the organisation of the workshop and changes in complementary

[11] The purpose was to avoid competitive bidding by firms for scarce workers. By contrast, employers were not forbidden to fire a worker. The asymmetry rankled some. The leaving certificates were repealed in October 1917.

[12] Rubin (1987) describes the workings of the Act in Glasgow. The Fabian Research Department claimed 'the effect of the Munitions of War Act, 1915, was to reduce the workers to a state bordering on slavery' (Drake, 1917, p. 26).

machinery. In one instance below, observations on hours and output are available for workers operating with two different types of physical capital and this will be recognised in the analysis. In other cases, the absence of changes in production methods and machinery is mentioned.[13] In most of data analysed below, the number of workers is constant (or, approximately, so) except in one case where the number of individuals at work varies across the shifts and this information will be taken into account. The data collected by the investigators were drawn from the 'wage sheets' and personnel records kept by the factories to determine their workers' wage payments and the employees were unaware that their work was examined by researchers. There is no reason to believe the workers altered their behaviour because they were the subject of analysis.

3. Hours and Output

There are three types of observations on the association between work hours and output. The first is a time-series of 122 weekly observations on the weekly output and average weekly work hours for workers on four jobs that range from 'heavy labour' to 'light labour'. The second type of observations consists of cross-section observations on the average weekly hours and average weekly output of shells of 43 individual women workers employed at two munition workshops. The third type of observations are diurnal data on hours worked over the day or over the night and the output produced each hour as hours at work increase. There are 77 hourly observations drawn from two workshops. Consider these three sets of observations in turn.

3.1. *Observations Over Time on Weekly Hours and Output of Four Groups of Workers*

The observations described in this subsection were collected by Vernon (1940, p. 16) and they describe the average weekly hours of work and weekly output of four groups of workers over approximately a year (1916) in a large factory in the Midlands: there are 56 weekly observations on about 100 women engaged in 'moderately heavy labour'; there are 26 weekly observations on another 40 women engaged in 'light labour'; there are 31 weekly observations on 56 men engaged in 'heavy labour'; and there are 9 weekly observations on 15 youths aged from 15 to 18 years engaged in 'light labour'.[14] The workers were employed in particular stages in the production of munitions and

[13] For 4½ months previously and during the period from which these data are drawn, no changes were made 'in the tools, the machinery, the nature of the operation or the quality of the alloy used' (Health of Munition Workers Committee, 1916, p. 18). Turnover caused the composition of the workers to change over this period although the majority of the workers at the beginning were present at the end. The report claimed 'in this particular operation, there was no appreciable difference between the output of the old experienced workers and of fresh and comparatively inexperienced workers' Health of Munition Workers (1916, p. 18).

[14] The task of the 100 women was that of turning fuse bodies, that of the 40 women was milling (grinding) a screw thread, that of the 56 men was sizing fuse bodies, and that of the 15 youths boring top caps. Horace Middleton Vernon (1870–1951) taught physiology at Oxford University. During a vacation in 1915 he worked in a shell factory in Birmingham and, later, volunteered his services to the HMWC. Subsequently, he worked for the Industrial Fatigue Research Board.

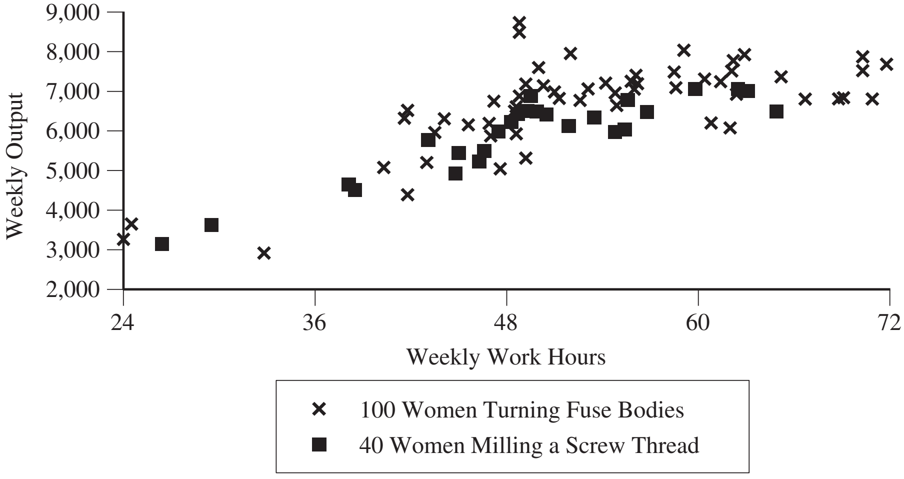

Fig. 1. *Weekly Output and Weekly Hours: 56 Observations on 100 Women Turning Fuse Bodies and 26 Observations on 40 Women Milling a Screw Thread on Fuse Bodies*

the output measure is an index number of their weekly output. A visual impression of the output-hours relation is provided by the scatter diagrams in Figure 1 on women and Figure 2 on men and youths.

These data are used to assess the following judgments of the HMWC: a shorter working week results in no loss of output and a seven-day work week harms output. With other data, the question of the relative productivity of day work and night work will be examined.

To take up these issues, initially, the four groups of workers were analysed separately and the relationship between their working hours and output was described by output-hours regressions in which hours were expressed in polynomials:

$$\text{Linear:}\quad X_t = \alpha_0 + \alpha_1 H_t + u_{1t}, \tag{1}$$

$$\text{Quadratic:}\quad X_t = \beta_0 + \beta_1 H_t + \beta_2 H_t^2 + u_{2t}, \tag{2}$$

$$\text{Cubic:}\quad X_t = \gamma_0 + \gamma_1 H_t + \gamma_2 H_t^2 + \gamma_3 H_t^2 + u_{3t}. \tag{3}$$

In these equations, X_t stands for output in week t, H_t is hours worked in week t and the u_{it} terms ($i = 1, 2, 3$) are stochastic components that embody unmeasured factors affecting output.

For each group of workers, the reduction in the calculated standard error of estimate of the equation suggests that the quadratic-in-hours and cubic-in-hours specifications are improvements in goodness of fit over the linear-in-hours specification. There was little to choose between the quadratic-in-hours and cubic-in-hours: both imply output rises with hours but at a decreasing rate. The similarity across these four groups of workers in the fitted output-hours relationships prompts the question of whether these weekly observations on all the workers may be pooled and a single output-hours regression fitted to the entire set (allowing each group to have its

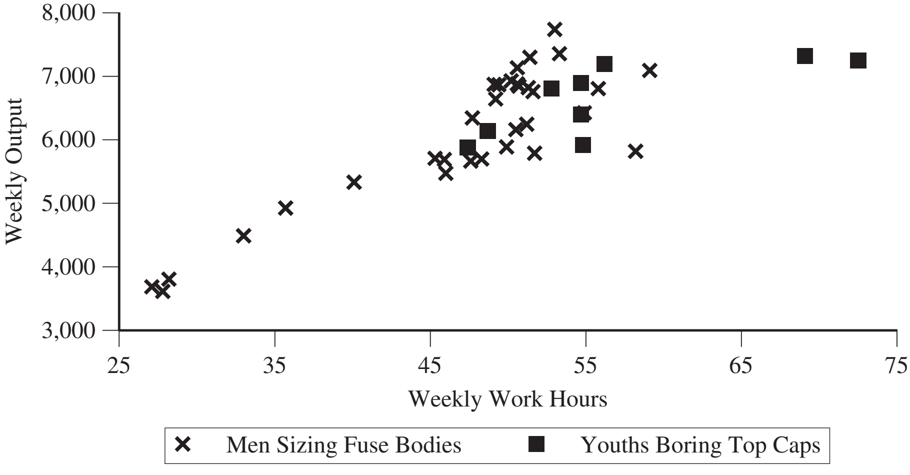

Fig. 2. *Weekly Output and Weekly Hours: 31 Observations on 56 Men Sizing Fuse Bodies and 9 Observations on 15 Youths Boring Top Caps*

own equation intercept). The least-squares estimates of the coefficients attached to the work hours variables in (1) to (3) fitted to all 122 weekly observations are reported in Table 1.[15]

The estimates of the quadratic-in-hours and the cubic-in-hours equations imply that output is a maximum at 67 and at 64 hours respectively. Because there are a few weeks in which actual observations on hours exceed 67 and 64, in these instances, observed hours were at levels where the estimated marginal product of hours is negative![16] However, there are relatively few of these estimated negative marginal products and a more guarded inference would be that, at hours above 60, output is not sensitive to changes in work hours.

Out of a concern that the equations fitted may not have provided sufficient flexibility to describe the output-hours relationship accurately, the observations were separated into two regimes: one regime corresponds to weekly hours less than 49 and the second regime consists of observations where hours are 49 or more. Spline functions were estimated that allow the output-hours relation at less than 49 working hours to differ from the output-hours relation at 49 hours and beyond. Separate quadratic-in-hours equations were estimated to the observations in the two hours regimes subject to the constraint that the two quadratic equations meet at 49 hours, the knot, where they also have the same derivatives. The knot was chosen at this value because working hours in many countries were reduced to 48 shortly after the War where it remained for two decades, suggesting it may have

[15] Applying conventional F-distribution tests, the null hypothesis that the slopes of the output-hours relation were the same for the four groups of workers could not be rejected by conventional criteria.

[16] When the quadratic and cubic equations are fitted to the four groups of workers separately, it is also the case that there are some observed hours of work that exceed the hours at which the estimated output-hours relation reaches a maximum. This is true for the women turning fuse bodies and the youths boring top caps.

Table 1

Least-squares Estimates of the Coefficients on Working Hours (and Estimated Standard Errors in Parentheses) of the Output-hours (1) to (3) Fitted to all 122 Weekly Observations

	Estimated coefficients (and estimated standard errors in parentheses) attached to variables listed in the first column		
RHS variable	Equation (1)	Equation (2)	Equation (3)
H_t	86.592	313.843	18.215
	(6.665)	(34.540)	(204.010)
H_t^2		−2.327	4.067
		(0.349)	(4.363)
H_t^3			−0.044
			(0.30)
H^{xmax}	ND	67.4	64.0
Goodness of fit statistics			
R^2	0.628	0.731	0.736
See	699.1	596.9	593.9

Notes. These equations include fixed effects that allow the intercept of the output-hours equation to be different for each group of workers. The same output-hours slope applies to all the workers. See is the standard error of estimate of the equation and H^{xmax} is the hours of work at which output reaches a maximum as implied by the estimates of the fitted equation. The form of (1) does not permit such a stationary value and ND means 'not defined'.

constituted a focal point.[17] To be explicit, the equation estimated is a quadratic-in-hours spline:

$$X_t = [a_1 + b_1(H_t - H_0) + c_1(H_t - H_0)^2]D_{1t} + [a_2 + b_2(H_t - H_1) + c_2(H_t - H_1)^2]D_{2t} + u_{4t}, \tag{4}$$

where D_{1t} takes the value of unity for observations where working hours are less than 49 and of zero otherwise while D_{2t} takes the value of unity for observations where working hours are 49 hours or more and of zero otherwise. H_0 is set to 24 weekly hours, the lowest value observed and H_1 is the knot of 49 hours. a_1 is allowed to be different for each of the four groups. The slope of the output-hours relation within each regime is restricted to be the same for workers in each group, a restriction that cannot be rejected by conventional tests. The least-squares estimates of the parameters on hours of work in (4) (the parameters b_1, c_1, b_2 and c_2) are reported in column *(i)* of Table 2.

The fitted output-hours spline resembles those curves implied by the equations in Table 1 except that the relationship in the regime corresponding to working hours less than 49 appears close to linear. Indeed, the estimated parameter on the quadratic term in this regime, c_1, though negative, is less (in absolute value) than its standard error. Re-estimating (4) with c_1 restricted to zero yields the estimates in column *(ii)* of

[17] A cubic-in-hours spline was also estimated but its output implications at very short hours and at very long hours were implausible. The implications of other knots were entertained with little consequence for the fitted output-hours relation. On 49 hours as the knot, 'some form of eight-hour [per day] legislation had been adopted by most western European countries by autumn 1919, and by most other industrial nations over the next two years. Meanwhile Britain, Italy and the US had moved to a 48-hour standard by collective agreements rather than legislation' (Scott and Spadavecchia, 2011, p. 1271).

Table 2

Least-squares Estimates of the Coefficients on Working Hours (and Estimated Standard Errors in Parentheses) of Output-hours Spline Functions Fitted to All 122 Weekly Observations

Parameters	Column (*i*) Quadratic-in-hours in both shorter hours and longer hours regimes	Column (*ii*) Linear-in-hours in shorter hours regime and quadratic-in-hours in longer hours regime	Column (*iii*)
<49 hours regime			
b_1	153.040	126.089	144.192
	(34.209)	(8.036)	(7.307)
c_1	−0.788	0*	0*
	(0.973)		
≥49 hours regime			
b_2	113.617	126.089	144.192
	(17.364)	(8.036)	(7.307)
c_2	−3.920	−4.533	−3.709
	(1.003)	(0.657)	(0.570)
Both hours regimes			
Sunday			−858.162
			(125.727)
H^{xmax}	63	63	68
Goodness of fit statistics			
R^2	0.738	0.736	0.812
See	592.16	591.28	500.98

Note. The asterisk denotes a constrained coefficient.

Table 2. When graphed, the fitted output-hours relations implied by the estimates in columns (*i*) and (*ii*) are virtually indistinguishable.

An implication of a linear relation between output and hours at hours less than 49 is that a log-linear fitted equation – as in (5) below – would yield a slope coefficient, δ_1, of unity:

$$\text{log-linear:}\ \ \ln(X_t) = \delta_0 + \delta_1 \ln(H_t) + u_{5t}. \tag{5}$$

The least-squares estimates of (5) (with fixed effects for each group of workers included) are contained in Table 3 where, for the shorter hours regime, the estimate of δ_1 is, indeed, unity.[18] The conclusion from the work presented in this Section is that the output-hours relation is decidedly non-linear: below 49 weekly hours, variations in output are proportional to variations in hours; for those observations corresponding to 49 or more hours, output rises with hours at a decreasing rate and a maximum of output occurs at about 63 hours. Output at 70 hours differs little from output at 56 hours and therefore, the HMWC's recommendations about the innocuous effects for output of hours' reductions are consistent with these estimates.

The total product curves estimated in columns (*i*) and (*ii*) of Table 2 imply a marginal product of hours that is constant with respect to hours until the knot at

[18] Recall from the introduction that Denison (1962) guessed that, in terms of (5), $\delta_1 \approx 0$ for hours at 49 and δ_1 = 0.6 for hours at 40. The estimates of δ_1 in Table 3 fitted to munition workers are not significantly different from Denison's value at 49 hours but exceed his guess for hours at 40.

Table 3

Least-squares Estimates of (5) $\ln(X_t) = \delta_0 + \delta_1 \ln(H_t) + u_{4t}$ *Fitted to all Observations, to Observations in the Shorter Hours Regime and to Observations in the Longer Hours Regime*

	Estimated coefficient (standard error in parentheses) on $\ln(H_t)$	Goodness of fit statistics	
		R^2	See
All 122 observations	0.794 (0.048)	0.725	0.110
Observations for hours <49	1.002 (0.087)	0.778	0.120
Observations for hours ≥49	0.172 (0.089)	0.218	0.076

Note. There are 47 observations in the regime of <49 hours and 75 observations in the regime of ≥49 hours.

49 hours after which it declines. The estimated marginal product of hours turns negative at 63 hours where output reaches a maximum. The average product of hours increases slightly with work hours at hours below 49 and reaches a maximum at 49 hours after which it falls as hours increase. Differences across hours in output per hour are small compared with differences in the marginal product of hours.[19]

3.1.1. *Sunday work*

The HMWC were very critical of a seven day working week. These data identify weeks when workers were employed on Sundays so that the HMWC's criticism may be evaluated. Naturally, those weeks involving Sunday work tended to be weeks with longer hours of work but sometimes a given number of weekly hours was packed into fewer work days so longer hours do not require Sunday work. Indeed, is it the case that, as the HMWC alleged, holding weekly hours constant, the absence of a rest day (Sunday) damages weekly output?

This question is addressed for each of the four groups of workers separately and for all of them pooled together. The results were the same for all specifications fitted, for the groups of workers analysed separately and for the workers pooled together. Here, simply one estimated equation is reported, that for the spline linear-in-hours below 49 hours and quadratic-in-hours at 49 hours and above. Column (*iii*) of Table 2 reports the results of adding a Sunday dummy variable to this specification.[20] The estimated coefficient is negative and significantly less than zero by conventional criteria. Indeed, in all regressions of output and hours estimated, the coefficient on the Sunday variable

[19] Surveying US firms heavily involved in aspects of armaments production in the Second World War, Brown and Baker (1942, p. 28) also identify 48 weekly hours as a threshold. They quote one executive: 'it is evident that 48 hours per week can be worked without ill effects either to the workman or the company's production'. By contrast, dissatisfaction with the length of the working week was expressed by many companies with schedules from 50 to 58 hours a week. Schedules of 60 hours or more were characterised by 'decreased productivity and increased absences, accidents and labour turnover' (p.33).

[20] To be precise, for almost all weeks, it is a dummy variable implying all workers were either working on Sunday or all workers were not working on Sunday. In a few cases, for youths, some of them worked on Sunday and some did not. In these few cases, the Sunday variable is a fraction, the fraction of workers who worked on Sunday. The estimates in column *(iii)* of Table 2 distinguish between seven-day working weeks and six-day working weeks (holding weekly hours constant). Aggregate production functions that differentiate between working hours per day and working days per week are fitted by Hamermesh (1996) using contemporary data.

is negative, significantly less than zero, while the shapes of the output-hours relation remain the same. The loss in output from denying workers a day of rest is about 10%.

The importance of a day of rest may be inferred from the comparison of the output consequences of two work schedules: one schedule involves work of ten hours a day for seven days or 70 weekly hours including work on Sunday; the other schedule entails work of eight hours per day for six days (and no work on Sunday) or 48 weekly hours. The second schedule became the norm in many countries soon after the War. Some munition workers were on the first schedule in 1914 and 1915. The estimates in column (*iii*) of Table 2 imply that output is slightly higher on the 48 hour working week (with no Sunday work) than on the seven-day work schedule. The difference is small (merely 1.4% of the 70 hour output) but it illustrates the relevance of a day of rest and the relative insensitivity of output to increases in working hours above 50 hours.

The importance for output of the elimination of Sunday labour speaks to the distinction between the effects of a shorter work day and the impact of an entire day of rest. There is some suggestion in the writings of the HMWC's investigators that not only were there immediate benefits to shorter hours, but also longer run advantages as workers fully adjusted to a shorter working week that involved a restorative day of rest.

3.2. *Cross-section Observations on Weekly Hours and Output of Individual Workers*

Although the data examined in the previous subsection consist of observations on the weekly output and weekly hours worked of groups of workers, the data considered in this section are observations on 43 individual women munition collected by Osborne (1919).[21] Her data on the average weekly output and the average weekly hours of work of individual women munition workers are from two workshops. Each workshop operated two different work schedules. The two schedules involved some individuals working at night and some during the day so her data provide an opportunity to compare day work with night work. A week of night work would alternate with a week of day work discontinuously. The shifts provided workers with one day of rest.[22]

The measure of output is the average number of shells produced by a worker per week. The weekly work hours of these women range from a low of 25 hours to a high of 63 hours with a central tendency not far from 40 hours. In other words, the work hours of these women tend to be lower than those workers described in the previous subsection perhaps because the work undertaken by these women was more demanding. Although only 18% of the 122 weekly observations analysed in the

[21] Osborne worked for two years for the Ministry of Munitions and, for a while, was the head supervisor in a munitions factory. She undertook investigations both for the HMWC and for the Industrial Fatigue Research Board. After the War, she emigrated to Australia and had an illustrious career there. Her brother served on the Western Front and was killed in action.

[22] The work in this study involved the 'ripping' or 'part off' operation in shell turning. Osborne (1919) writes, 'The operation is generally considered to be the hardest in shell-making for the shell is at its heaviest stage; and, further, the operation is a rapid one and entails constant changing of shells. In the case of the six inch shell the operation is particularly heavy ... as the forging at this stage weighs about 140 lbs., the handling by pulleys of this amount of material into and out of the lathe constitutes a strenuous day's work'. The women under study had worked on these operations for a period of about 18 months, on shifts of 12 hours duration.

Table 4

Least-squares Estimates of the Slope Coefficients (and Estimated Standard Errors in Parentheses) of Output-hours Equations Fitted to Observations on 43 Women

	Dependent variable is			
	X_i	X_i	X_i	$\ln(X_i)$
	Equation (1)	Equation (2)	Equation (3)	Equation (5)
RHS variable	Estimated coefficients (and estimated standard errors in parentheses) attached to variables listed in the first column			
H_i	7.374 (0.494)	12.406 (5.852)	69.742 (31.684)	
H_i^2		−0.055 (0.063)	−1.385 (0.726)	
H_i^3			0.010 (0.005)	
$\ln(H_i)$				0.898 (0.057)
H^{xmax}	ND	Beyond observed hours		ND
Goodness of fit statistics				
R^2	0.845	0.847	0.860	0.852
See	37.879	37.998	36.914	0.099

Notes. Estimates of (2) and (3) imply a maximum of output beyond those hours observed by these workers.

previous subsection were observations where hours were equal to or less than 45 hours, 58% of these observations on individual women record weekly hours of 45 or less.

To describe the data on each worker's weekly work hours and her weekly production of shells, the equations specified in the previous subsection – (1) to (5) – were fitted to the output and hours observations. The estimated coefficients on the hours variables are listed in Table 4.[23] In this instance, the quadratic specification appears little different from the linear specification though the cubic represents a better fit. When graphed, the implications of the estimates for the output-hours relation of all three specifications and of the log-linear equation are almost coincident: for these workers at this activity, a linear output-hours relation provides a compact description of these observations. In addition, the coefficient attached to ln H_i in the log-linear specification is not significantly different from unity and thereby consistent with the hypothesis that the marginal product of hours is independent of work hours. In other words, most of the observations on these individual women are in the hours regime corresponding to less than 49 weekly hours which was described, in the previous subsection, by a linear output-hours relationship. The finding of a linear output-hours relation for these individual women is, therefore, consistent with the results in the previous subsection.

Is there a difference between the output-hours association of the 27 women working during the day and the 16 women working at night? Separate least-squares estimates of

[23] The estimates corresponding to the quadratic-in-hours spline are not reported as the coefficient on the quadratic term for the regime corresponding to 49 or more hours was smaller than its standard error and the estimated marginal product of hours was mildly rising at long hours.

the output-hours relation are derived from which the simulations show the output of the night workers to be slightly above that of the day workers at hours observed for both day and night workers. The difference is negligible. Indeed, a formal test of the hypothesis that the output-hours equation for night workers is no different from that of day workers cannot be rejected. This finding holds for the estimates of the quadratic, cubic and log-linear equations as well as for the linear. This supports the HMWC's conclusion that, on the discontinuous system of alternating a week of day work with a week of night work, there is no significant difference between output on the night and day shifts and, if anything, output is higher on the night shifts.

3.3. *Hours and Output Over the Day and Over the Night*

In addition to the observations on weekly output and weekly work hours on individual women workers described in the previous subsection, Osborne reported on the output of groups of women each hour of the day or night. These women were engaged in the same operation of shell production as those women described in the previous subsection. With the data investigated in this section, not only does Osborne supply information on shells produced during each hour of the shift, she also provides data on the number of women workers. Moreover, her period of observation spans a time when new machinery was introduced that made the work less onerous.[24] Consequently, some of her hours and output observations are from a time before the new machinery was introduced and some observations are taken after the new machinery has been installed. The output-hours relation will be described taking account of variations in two other inputs: the number of workers and the vintage of the machinery.

There are 77 hourly observations on output, 33 of them on the day shift and 44 on the night shift. Each shift involves 10½ hours of actual work.[25] The workshops maintained the discontinuous system described earlier whereby a week of night work would be followed by a week of day work. This means that the night and day observations on output are on the same workers. The workers had one day each week of not working.

Is there an evidence of fatigue in the output of these workers? That is, as hours of work lengthen over the day and night, after a point, do women produce less each hour. If x_j is the output of shells during the jth hour since work started on a shift and if h_j denotes hours worked (excluding any break) since the beginning of work, after a point, does x_j fall as the duration of work hours lengthen? Defining the marginal product of hours as the amount added to total product by working one more hour, then x_j is a discrete measure of the marginal product of hour j. Therefore, asking

[24] The new machines 'considerably reduced the demands made on the women for violent physical exertion. The old system of chuck and crowbar clamping was replaced by a jaw clamp, in which the shell forging was comparatively easily fixed, and the violent jerks necessary to secure the forging were no longer required. Further, the level at which the shell was fixed was lower and more convenient for the women workers. Lastly, the cutting itself was automatic, whereas formerly the tool required constant guidance by the operator. In spite of these modifications, this operation was still considered very heavy' (Osborne, 1919, p. 4).

[25] The day shift starts at 6.00 a.m. and ends at 6.00 p.m.; there is a mid-morning break of half-an-hour and an hour's meal break from 1.00 to 2.00 p.m. The night shift starts at 6.00 p.m. and ends at 6.00 a.m. There is a break from 9.00 to 10.00 p.m. and another break from 1.30 to 2.00 a.m.

whether x_j falls as h_j increases is tantamount to asking whether the law of diminishing returns holds for work hours.

The following equations were estimated to these observations on output each hour and the number of hours worked since the beginning of the day or night:

$$\text{Linear: } x_j = \mu_0 + \mu_1 h_j + \mu_2 M_j + \mu_3 K_j + \mu_4 N_j + u_{6j}, \tag{6}$$

$$\text{Quadratic: } x_j = \eta_0 + \eta_1 h_j + \eta_2 h_j^2 + \eta_3 M_j + \eta_4 K_j + \eta_5 N_j + u_{7j}, \tag{7}$$

$$\text{Cubic: } x_j = v_0 + v_1 h_j + v_2 h_j^2 + v_3 h_j^3 + v_4 M_j + v_5 K_j + v_6 N_j + u_{8j}, \tag{8}$$

$$\text{Log-linear: } \ln(x_j) = \lambda_0 + \lambda_1 \ln(h_j) + \lambda_2 M_j + \lambda_3 K_j + \lambda_4 N_j + u_{9j}. \tag{9}$$

M_j denotes the number of workers at work during hour j, K_j is a dummy variable that takes the value of unity when the work is performed with the newer vintage of machinery and of zero otherwise, and N_j is a dummy variable that takes the value of unity for an observation from the night shift and of zero otherwise. The u_{ij} terms (i = 6, 7, 8, 9) are stochastic components incorporating the effects of omitted variables.

The least-squares estimates of the parameters of (6) to (9) as fitted to all 77 (Day plus Night) observations are reported in Table 5. The linear and log-linear specifications imply marginal products that decline throughout the shift, whereas the other equations have an interval of initially rising marginal products before they turn down (after about 4½ hours for the quadratic specification and after about 6 hours for the cubic equation). In short, these estimates of the marginal product of hours over the day and night take the form that are often drawn in textbooks: when the functional form permits, the marginal product of hours worked rises with hours and then, when diminishing returns set in, declines. In these data, the region of diminishing marginal product operates over much of the working day. However, marginal products never turn negative so that a shorter working day implies a loss of output (holding constant the number of working days).

In all cases, the marginal product of hours over the day or night is a positive function of employment (M_j) and is higher when the newer vintage machinery (K_j) is used.[26] The estimated coefficient on the night shift dichotomous variable (N_j) is always positive and significantly greater than zero. According to the log-linear estimates, output per hour is about 18% higher when the workers use the new machinery and about 9% higher on the night shift over the day shift. To pursue the day-night distinction, (6) to (9) were fitted to the day and night observations separately with estimates reported in Table 6. The shape of the estimated marginal product of hours over the day and night are similar except the marginal product of hours worked at night is clearly larger than that of hours worked during the day.[27] Again the simulated relations corresponding to the estimates of (7) are pictured as Figure A7 in the online Appendix A.

[26] If, say, (7) describes movements in the marginal product of hours, as maintained, then, upon integration, the implied production function is a cubic-in-hours and hours are interacted with employment and capital.

[27] Allowing the output-hours relationship to differ between the hours worked before the one hour break in mid-shift and the hours worked after this break did not result in any clear implications.

Table 5

Least-squares Estimates of Output of Shells per Hour Regressed on Hours Worked Since Starting Work and Other Variables: 77 Pooled Day and Night Observations

	Dependent variable is			
	x_j	x_j	x_j	$\ln(x_j)$
	Equation (6)	Equation (7)	Equation (8)	Equation (9)
RHS variable	Estimated coefficients (and estimated standard errors in parentheses) attached to variables listed in the first column			
h_j	−3.893	12.991	−10.294	
	(1.128)	(4.400)	(12.821)	
h_j^2		−1.465	3.363	
		(0.371)	(2.529)	
h_j^3			−0.279	
			(0.145)	
$\ln(h_j)$				−0.060
				(0.024)
h DR	1	4.4	6	1
M_j	6.117	6.262	6.295	0.031
	(0.558)	(0.510)	(0.501)	(0.003)
K_j	35.706	36.339	36.351	0.167
	(7.343)	(6.699)	(6.574)	(0.036)
N_j	16.970	16.460	16.213	0.088
	(6.818)	(6.219)	(6.105)	(0.033)
Goodness of fit statistics				
R^2	0.711	0.763	0.775	0.720
See	28.62	26.097	25.611	0.139

Note. hDR denotes the hours since starting work when diminishing returns set in.

3.4. *Some Conclusions about Hours and Output of Munition Workers*

The estimates above on the output-hours relationship suggest that, for most workers, weekly output rises with weekly hours of work although, after a point, the increase in output declines as more hours are worked. For hours of 48 or less, weekly output tends to be proportional to weekly hours worked and the decline in the marginal product of hours occurs after 48 weekly hours. The decline in marginal products is not clear for the cross-section observations on 43 individual women where a linear output-hours representation describes the data well at all observed hours. Although a concave-from-below output-hours relation is common at long hours, the particular shape of the relation varies across workers and across types of work.

The diurnal data on the additional output produced in an hour are interpreted as observations on a discrete measure of the marginal product of hours worked over the day or night. These observations describe marginal products as rising over the first few hours of work and then declining.

These findings are broadly consistent with the HMWC's recommendations. Increases in output as hours rise beyond 50 in a week are relatively small so that the sorts of reductions in weekly hours and in daily hours that the HMWC urged would have implied small reductions in output. A reduction in working time effected by eliminating working on Sunday would have had positive consequences for output. The absence of a day of

Table 6

Least-squares Estimates of Output of Shells per Hour Regressed on Hours Worked Since Starting Work and Other Variables: Fitted to Night and Day Observations Separately

	Dependent variable is							
	x_j		x_j		x_j		$\ln(x_j)$	
	Equation (6)		Equation (7)		Equation (8)		Equation (9)	
RHS variable	Day	Night	Day	Night	Day	Night	Day	Night
	Estimated coefficients (and estimated standard errors in parentheses) attached to variables listed in the first column							
h_j	−4.311	−3.662	11.278	13.947	1.982	−20.356		
	(1.291)	(1.747)	(4.604)	(7.063)	(13.633)	(20.560)		
h_j^2			−1.351	−1.528	0.580	5.570		
			(0.388)	(0.596)	(2.691)	(4.051)		
h_j^3					−0.112	−0.410		
					(0.154)	(0.232)		
$\ln(h_j)$							−0.058	−0.064
							(0.031)	(0.035)
hDR	1	1	4	5	5	6	1	1
M_j	6.147	5.587	6.225	5.920	6.248	5.900	0.033	0.027
	(0.557)	(1.197)	(0.491)	(1.129)	(0.496)	(1.099)	(0.003)	(0.006)
K_j	31.910	37.837	32.453	38.261	32.553	38.237	0.165	0.175
	(10.258)	(10.306)	(8.718)	(9.658)	(8.794)	(9.404)	(0.058)	(0.048)
Goodness of fit statistics								
R^2	0.867	0.492	0.908	0.565	0.909	0.598	0.843	0.497
See	20.928	33.807	17.785	31.674	17.937	30.841	0.118	0.156

Note. *hDR* denotes the hours since starting work when diminishing returns set in.

rest each week had damaging effects on output, as the HMWC affirmed. The HMWC believed that night work was no less productive – and, possibly, more productive – than day work provided the work schedule alternated a week of night work with a week of day work. Our results confirm the Committee's judgment. The reason for this superior output at night is not due to an evident selection effect – more efficient workers choosing to or assigned to work on the night shift – because these are the same individuals who are working one week during the day and the next week at night.

4. Implications of the Productivity of Working Hours

With movements in the demand for hours derived principally from variations in the military's demands for munitions and its preparations for conflict, the output-hours relation fitted in the previous Section has the interpretation of a production function. Within the hours observed, the marginal product of hours declines with respect to hours. This implies that the sensible employer will not be indifferent to the length of his employees' working hours. This raises issues of identification for other branches of economics research.

There is a large empirical literature in economics in which researchers relate observations on the hours of market work of individuals to observations on their hourly earnings and other variables and in which the fitted relationship is interpreted as a labour supply function. Rarely is the basic identification question addressed: as a quantity (hours) and price (wage) relationship, why is this equation a supply function and not a demand function or some hybrid relation?

This was taken up by Lewis (1957) in an article written almost 60 years ago in which he offered an explanation for the decline in the length of the working week since the end of the nineteenth century. Although the real wages of production workers in US manufacturing industry follow an upwards trend (until the 1970s), average weekly hours of work decline until the Second World War and exhibit little or no trend after 1950. Writing in the 1950s, to account for these movements, Lewis suggested that, 'to a first approximation', in a figure with the real wage on the vertical axis and the hours worked by an individual on the horizontal axis, the typical employer's demand for work hours is infinitely elastic at a given wage rate. According to Lewis, the typical employer cares about the aggregate hours worked by the firm's entire work force but, at the given wage, the employer allows each worker to set his or her own work hours according to the worker's income-leisure preferences. This horizontal demand curve for working hours shifted up over time as the economy grew, real incomes rose and the derived demand for labour increased. The fact that, as wages rose, hours fell (at least until 1940) implies, with an assumed unchanged labour supply curve, that this supply curve is negatively sloped and the income effect of wage increases exceeds the substitution effect. This was Lewis's justification for interpreting a regression of the hours of work of individuals on their real wages as a labour supply function.

A decade later, Lewis (1969) wrote another article on work hours that was published in a Spanish-language journal. An English-language version of this article titled 'Employer's Interests in Employee's Hours of Work' has circulated for over 40 years. In this later article, Lewis replaced his earlier framework with one in which an employer did care about the hours worked by each employee. The amendment that generated this change was to distinguish between a firm's labour costs that vary with the number of workers employed and labour costs that varied with hours of work. Others have called this a distinction between fixed and variable labour costs.[28]

This article has considered a different reason for an employer not to be indifferent to the work hours of each employee, namely, the diminishing productivity associated with an individual working long hours. The findings here suggest Lewis's hypothesis that output is proportional to working hours is, indeed, an appropriate 'first-order approximation' to working hours – up to a certain threshold. Beyond this threshold, increases in working hours raise output at a diminishing rate. This applies to hours worked over the week and to hours worked over the day. The working week threshold for the munition workers considered in this article was at about 49 hours, but for other workers it may be more or less.

If this 49 hours threshold applied also to US manufacturing workers, then Lewis's assumed horizontal marginal product of hours curve does not apply to the period

[28] Lewis (1969, p. 42) described those costs that are independent of hours worked as including 'the costs of searching for and recruiting employees, maintaining payroll and other records for them. Orienting them to the foibles of their work and work environment, supervising and policing their work and so on'.

before 1920 because, in these years, the average weekly hours of production workers in US manufacturing industry exceeded 48. Instead, the demand for hours function is kinked at about 48 hours: at hours less than 49, the demand for hours is that suggested by Lewis, a horizontal schedule expressing an employer's indifference to the number of hours worked by an employee; at hours of 49 or more, the marginal product of hours falls as hours lengthen.

If the firm is a price-taker in labour markets and the supply of hours schedule is horizontal (the worker is willing to work any hours the employer demands), the wage is set by the location of the supply of hours function and work hours are determined by the employer's demand for hours, the reverse of the situation posed by Lewis.[29] If the horizontal supply of hours function moves up over time because of competition among firms for the hours of workers or because of trade union pressure on wages or because of minimum wage regulation, the hours-wage observations trace out the firm's negatively sloped hours demand function, not a negatively sloped supply of hours function, as Lewis proposed in 1957.

In fact, suppose that, over the years 1890–1920, the output-hours relationship follows the quadratic-in-hours (2). Then the profit-maximising firm's first-order condition for working hours can be written as $H_t = \theta_0 + \theta_1 \ (w/p)_t$ where $\theta_1 = (2\beta_2)^{-1}$. When the stochastic version of this first-order condition is fitted to the 1890–1920 annual observations on US manufacturing weekly hours and real hourly compensation, the estimated value of θ_1 is -7.629 (0.656) which implies a value of -0.066 for β_2.[30] The elasticity of demand for hours with respect to wages is -0.267 evaluated at mean hours and wages.

The outcome sketched in the previous paragraph – where the labour supply curve is infinitely elastic – is not the most likely setting. More plausible is the case in which the hours of work supply function is not horizontal but one in which the work hours supplied to a firm by a typical worker is responsive to changes in wages. In this case, hours of work are a function both of variables that shift the employer's marginal revenue product of hours of work and the worker's supply of work hours and the identification of one or other relationship is not straightforward.

5. Conclusions

This re-examination of the recommendations relating to hours of work of the HMWC finds them broadly consistent with our analysis: at the levels of working hours in 1915 and 1916 during the War, hours reductions would have had small or no damaging effects on output; those weeks without a day of rest from work had about 10% lower output than weeks when there was no work on Sunday holding weekly hours constant; night work was not less productive than day work and, indeed, may have been slightly more productive.

[29] This reversal of Lewis' horizontal demand function for hours with a horizontal supply function of hours was entertained also by Ehrenberg (1971).

[30] The hourly compensation data are drawn from Officer (2009, Table 7.7, p. 170) and the weekly hours series from Jones (1963).

Long weekly hours and long daily hours do not necessarily yield high output and this implies that, for some employees engaged in certain types of work, the orthodox optimising employer will not be indifferent to the length of their working hours over a day or week. This point has already been made in the literature on fixed employment costs where costs linked to the number of workers employed inclines a firm to extend the working hours of employees. This article has suggested a different reason for an optimising employer to care about the length of working hours: employees at work for a long time experience fatigue or stress that not only reduces his or her productivity but also increases the probability of errors, accidents and sickness that impose costs on the employer.

Unlike the case of fixed employment costs, these concerns over work stress incline the firm not to extend the work hours of employees but to curtail them. The point at which fatigue sets in and the nature of the link between working hours and work effort or fatigue are likely to vary across types of work and across workers.

This is not a new argument,[31] but it seems to have been neglected in contemporary models of labour markets. It also implies that restrictions on working hours – those imposed by statute or those induced by setting penalty rates of pay for hours worked beyond a threshold or those embodied in collective bargaining agreements – may be viewed not as damaging restraints on management but as an enlightened form of improving the workplace efficiency and welfare.

However, why should an employer resist cutting working hours: if workers' earnings are tied to their hours of work, then fewer hours imply lower labour costs and, if shorter hours yield the same output, why would any firm knowingly select the higher hours? Even if workers are paid entirely by results, there are ancillary costs of long working hours such as the expenses of running complementary machinery and of providing light, heat, ventilation and supervisory labour. Is it possible that employers were unaware that hours could be reduced without loss of output?[32] Or that the costs of a trial period of shorter hours deterred employers from experimenting with them?

As for the measurement of the labour input in production, although it may be a useful simplification to combine the number of workers and their average hours of work into a single variable, worker-hours, there is also a case for unbundling them and for allowing working hours to enter production differently from the number of workers. Moreover, the use of average hours may be troublesome if there are

[31] At one time, it was sufficiently familiar and accepted to be discussed in text books as, for example, in Reynolds (1954, pp. 252–61).

[32] This was the opinion of Hicks (1932, 1963, ch. V) who believed that 'probably it has never entered the heads of most employers that it was at all conceivable that hours could be shortened and output maintained. But it is clear that there were a few who had realised it (Robert Owen, for instance, p. 107)'. McIvor (1987) records the implausible arguments with which the engineering confederation of employers dismissed the effects of Mather's hours reductions (as mentioned in the Introduction). Similarly, Vernon (1940, p. 7) believed many employers lacked knowledge of these relationships: 'in spite of what employers might reasonably have been expected to know about the physical capabilities of their workers in the munition factories of 1914–8, they in many cases acted in direct opposition to the well-supported evidence supplied by earlier investigations, and subjected their employees to unwarrantable conditions of work'.

differences among workers in their hours and if the results in this article apply; in this case, the average may be an especially inappropriate summary indicator of a highly non-linear effect. At 35 hours, an additional five hours to the length of the working week has consequences for the effective labour input that may be quite different from an additional five hours starting at 48 hours.

This argument also implies that the conventional procedure in estimating labour supply functions with observations on work hours and wages is frustrated by the familiar identification problem of distinguishing the supply function from the demand function in quantity (hours) and price (wage) observations.

Do the HMWC's concerns about long work hours have any relevance for today's workplaces? A number of recent studies show that accidents and illnesses follow long work hours. For instance, an analysis of over ten thousand workers from the National Longitudinal Survey of Youth between 1987 and 2000 found that, holding constant a number of other factors, those who worked at least twelve hours each day or at least sixty hours per week had considerably higher (37% and 23% respectively) injury hazard rates than other workers. In five metal production plants between 1999 and 2002, the conditional probability of a work-related injury rose with hours at work (Vegso *et al.*, 2007).

Long hours typify certain jobs and research has documented untoward consequences of long hours in these occupations. In a study of hospital staff nurses, shifts longer than 12 hours and working weeks longer than 40 hours were associated with significantly heightened probabilities of error that raised questions about patient safety. In another study, medical interns were significantly more likely to be involved in motor vehicle crashes if they had just worked extended shifts.[33] Similar reports have been made about airline pilots, police officers, truck drivers and soldiers.

Work fatigue and work stress are not confined to these occupations. In a nationally representative survey of almost 30,000 US workers interviewed between August 2001 and May 2003, almost 38% replied affirmatively to the question, 'Did you have low levels of energy, poor sleep or a feeling of fatigue in the past two weeks?' Full-time workers were more likely to lose productive time from fatigue than those working part-time. In addition, in 2002, according to the Health and Retirement Survey, one-fifth of workers aged 55–60 years strongly agreed with the description of their current job as involving 'a lot of stress'.

It would be valuable if the analysis here could be repeated on contemporary data that contain information on workers' output and their working hours. Then we might be in a better position to assess Denison's (1962, p. 39) judgment that 'Few studies offer more promise of adding to welfare and contributing to wise decisions in a matter that may greatly affect the future growth rate than a really thorough investigation of the present relationship between hours and output. Such an investigation would deal

[33] The studies in this and the next paragraph are found in Johnson (2004), Rogers *et al.* (2004), Barger *et al.* (2005), Dembe *et al.* (2005), Ricci *et al.* (2007) and Rho (2010).

with a wide variety of occupations and industries operating under different conditions'.

Stanford University

Additional Supporting Information may be found in the online version of this article:

Appendix A. Additional Tables and Figures

References

Agnew, T.H. (1917). 'Report on the health and physical condition of male munition workers', Interim Report of the Health of Munition Workers Committee, Cmd. 8511.

Bandiera, O., Barankay, I. and Rasul, I. (2011). 'Field experiments with firms', *Journal of Economic Perspectives*, vol. 25(3), pp. 63–82.

Barger, L.K., Cade, B.E., Ayas, N.T., Cronin, J.W., Rosner, B., Speizer, F. and Czeisier, C.A. (2005). 'Extended work shifts and the risk of motor vehicle crashes among interns', *New England Journal of Medicine*, vol. 352 (2), pp. 125–34.

Barker, P. (1992). *Regeneration*, London: Penguin Books.

Brown, D.G. (1965). 'Hours and output' in (C.E. Dankert, F.C. Mann and H.R. Northrup, eds.), *Hours of Work*, Industrial Relations Research Association, Publication No. 32, pp. 147–60, New York: Harper & Row.

Brown, J.D. and Baker, H. (1942). *Optimum Hours of Work in War Production*, Princeton, NJ: Princeton University.

Campbell, J.M. and Wilson, L.E. (1917). 'Inquiry into the health of women engaged in munition factories', Interim Report of the Health of Munition Workers Committee, Cmd. 8511.

Dembe, A.E., Erickson, J.B., Delbos, R.G. and Banks, S.M. (2005). 'The impact of overtime and long work hours on occupational injuries and illnesses; new evidence from the United States', *Occupational and Environmental Medicine*, vol. 62(9), pp. 588–97.

Denison, E.F. (1962). *The Sources of Economic Growth in the United States and the Alternatives Before Us*, New York: Committee for Economic Development.

Drake, B. (1917). *Women in the Engineering Trades*, London: George Allen & Unwin.

Ehrenberg, R.G. (1971). *Fringe Benefits and Overtime Behavior*, Lexington, DC: Heath and Co.

Feldstein, M.S. (1967). 'Specification of the labour input in the aggregate production function', *Review of Economic Studies*, vol. 34(4), pp. 375–86.

Goldmark, J. (1912). *Fatigue and Efficiency: A Study in Industry*, New York: Russell Sage Foundation.

Hamermesh, D.S. (1993). *Labour Demand*, Princeton, NJ: Princeton University Press.

Hamermesh, D.S. (1996). *Workdays, Workhours and Work Schedules: Evidence for the United States and Germany*, Kalamazoo, MI: Upjohn Institute.

Harrison, G.W. and List, J.A. (2004). 'Field experiments', *Journal of Economic Literature*, vol. 42(4), pp. 1009–53.

Hart, R.A. (2007). 'Women doing men's work and women doing women's work: female work and pay in British wartime engineering', *Explorations in Economic History*, vol. 44(1), pp. 114–30.

Hart, R.A. and McGregor, P.G. (1988). 'The returns to labour services in West German manufacturing industry', *European Economic Review*, vol. 32(4), pp. 947–63.

Health of Munition Workers Committee. (1916). Statistical information concerning output in relation to hours of work, Memorandum No. 12 Cmd. 8344.

Health of Munition Workers Committee. (1919). Final Report, Cmd. 9065.

Hicks, J.R. (1932, 1963). *The Theory of Wages*, London: Macmillan.

Johnson, R.W. (2004). 'Trends in job demands among older workers, 1992–2002', *Monthly Labor Review*, vol. 127(7), pp. 48–56.

Jones, E.B. (1963). 'New estimates of hours of work per week and hourly earnings, 1900–1957', *Review of Economics and Statistics*, vol. 45(4), pp. 374–85.

Kossoris, M.D. and Kohler, R.F. (1947). *Hours of Work and Output*, Washington, DC: US Department of Labor, Bureau of Labor Statistics, Bulletin No. 917.

Leslie, D. and Wise, J. (1980). 'The productivity of hours in UK manufacturing and production industries', Economic Journal, vol. 90(357), pp. 74–84.

Lewis, H.G. (1957). 'Hours of work and hours of leisure', in (L. Reed Tripp, ed.), *Proceedings of the Ninth Annual Meeting of the Industrial Relations Research Association*, pp. 196–206. Madison, WI: Industrial Relations Research Association.

Lewis, H.G. (1969). 'Employer interests in employee hours of work' [Interes del empleador en las horas de Trabajo del empleado]', *Cuadernos de Economia*, vol. 6(18), pp. 38–54.
Loveday, T. (1917). 'The causes and conditions of lost time', Health of Munition Workers Committee, Interim Report: Industrial Efficiency and Fatigue, Cmd. 8511, pp 41–67.
Marti, M. (2000). 'Substitution between working hours and employment: an empirical analysis for Switzerland', *Swiss Journal of Economics and Statistics*, vol. 136(3), pp. 397–415.
Matthews, R.C.O., Feinstein, C.H. and Odling-Smee, J.C. (1982). *British Economic Growth 1856–1973*, Stanford, CA: Stanford University Press.
McIvor, A.J. (1987). 'Employers, the government, and industrial fatigue in Britain, 1890–1918', *British Journal of Industrial Medicine*, vol. 44(11), pp. 724–32.
Officer, L.H. (2009). *Two Centuries of Compensation for US Production Workers in Manufacturing*, New York: Palgrave Macmillan.
Osborne, E.E. (1919). 'The output of women workers in relation to hours of work in shell-making', Report No. 2, Industrial Fatigue Research Board, London.
Reynolds, L.G. (1954). *Labor Economics and Labor Relations* (2nd edn), New York: Prentice-Hall.
Rho, H.J. (2010). *Hard Work? Patterns in Physically Demanding Labor among Older Workers*, Washington, DC: Center for Economic and Policy Research.
Ricci, J.A., Chee, E., Lorandeau, A.L. and Berger, J. (2007). 'Fatigue in the US workforce: prevalence and implications for lost productive work time', *Journal of Occupational and Environmental Medicine*, vol. 49(1), pp. 1–10.
Rogers, A.E., Hwang, W.-T., Scott, L.D., Aiken, L.H. and Dinges, D.F. (2004). 'The working hours of hospital staff nurses and patient safety', *Health Affairs*, vol. 23(4), pp. 202–12.
Rubin, G.R. (1987). *War, Law, and Labour: The Munition Acts, State Regulation, and the Unions, 1915–1921*, Oxford: Clarendon Press.
Scott, P. and Spadavecchia, A. (2011). 'Did the 48-hour week damage Britain's industrial competitiveness?', *Economic History Review*, vol. 64(4), pp. 1266–88.
Vegso, S., Cantlet, L., Slade, M., Taiwo, O., Sircar, K., Rabinowitz, R., Fiellin, M., Russi, M.B. and Cullen, M.R. (2007). 'Extended work hours and risk of acute occupational injury: a case crossover study of workers in manufacturing', *American Journal of Industrial Medicine*, vol. 50(8), pp. 597–603.
Vernon, H.M. (1940). *The Health and Efficiency of Munition Workers*, London: Oxford University Press.
Woollacott, A. (1994). *On Her Their Lives Depend: Munitions Workers in the Great War*, Berkeley, CA: University of California Press.