The Work of British Women Mathematicians during the First World War

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There is no doubt that the First World War acted as a catalyst to provide women with unique opportunities to infiltrate the male-dominated bastion of industrial engineering. This was particularly apparent at the establishments intimately involved in the advancement of the fledgling discipline of aeronautics and its related fields. The Royal Aircraft Factory (RAF) lay at the centre of the research and development that was driving innovation in aeronautics in Britain, and the facility was responsible for the design and testing of new aircraft for operational use by the Royal Flying Corps (RFC). The National Physical Laboratory (NPL) focused more on the theoretical aspects of aerodynamics. Its primary weapon in this pursuit was the analysis of data obtained from the observation of the behaviour of scale models of aircraft, or aircraft components, in wind tunnels. In London, a department in the British Admiralty was formed specifically to address issues pertaining to the strength and integrity of aircraft structures. Within all three of these domains there was a great demand for individuals who had a background and expertise in mathematics and, as increasing numbers of men were conscripted to bolster the front line, this requirement was mitigated by the employment and deployment of suitably qualified women. This was a fact that did not go unnoticed by the press, as evidenced by comments in *The Times* of London.[1]

But as much as the war provided a stimulus for the development of aeronautics, it was also a fillip for the development of ballistics, notably anti-aircraft gunnery. While staff at the RAF and the NPL were engaged in developing ever more sophisticated aircraft, their counterparts employed by the Munitions Inventions Department and based at HMS Excellent at Whale Island, near Portsmouth, aided by the Karl Pearson and his ‘computers’ at University College London (UCL), were producing a stream of high-angle range tables for gunnery. Pearson had employed women in his laboratories before the War but work generated by the conflict led many of these women into new fields as well as bringing them into his workforce.

The majority of the women mathematicians engaged in such work were educated at either Cambridge University, or at one of a number of colleges in the London area that were affiliated to the University of London. There were two main reasons for this, one academic and the other geographic. Much of the mathematics required for application to aerodynamics is relatively complex and, at that time, those women able to meet the exacting demands of a Cambridge education in the subject were the most likely to be able to offer a meaningful academic contribution to the ongoing aeronautical research. But there were practical considerations too. Since the Admiralty, RAF, and NPL were all located in and around London, it made sense to source staff from suitable candidates educated and living in the surrounding area.

Pivotal Centres of Higher Education in Mathematics for Women 1870–1918

During the 19th century, Cambridge University was the fulcrum of British mathematics, and its Mathematical Tripos the most prestigious and demanding examination in Britain. It was punishingly hard, both physically and mentally – students often broke down while studying for it or during the examination itself – but the rewards were great. The order of merit was reported nationally and students who came high on the list of wranglers (those in the first class) had a passport to the career of their choice, be it the law, the Church, medicine, mathematics, or on whatever they set their sights. (Neal, 1907; Barrow-Green, 2019) It is hard to over-estimate the kudos attached to being the Senior Wrangler, cachet that went far beyond the bounds of the University.

From the middle of the second half of the century, women could study mathematics at Cambridge – the women's colleges Girton and Newnham were founded in 1869 and 1872 respectively – but they had to obtain permission to sit the Tripos examination, they could not do so by right, and they could not be awarded a degree with its associated privileges and voting rights. For over three-quarters of a century the two colleges were not even officially part of the University; they would have to wait until 1948 to enjoy this status. That is not to say that all Cambridge men were against women studying mathematics, and indeed some of them would travel to Girton or Newnham to hold classes or to give private tuition, or 'coaching' as it was called.[2]

Initially, the women studying mathematics caused little stir. But in 1880 when Charlotte Scott was judged equal to the eighth-wrangler she created a sensation. The newspapers and periodicals were full of her success – she had done better than 93 of the 102 men taking the examination. Scott's achievement generated a growth in support for women students and from 1881 women were given the right to take the Tripos examination and to have their results published, albeit separately from the men. They were still prohibited from being awarded degrees however. Ten years later, there was an even greater sensation when Philippa Fawcett was judged to be above the senior wrangler, reports being published as far afield as *The New York Times*.[3]

She had scored 13% more marks than the highest ranked man, G.T. Bennett, achieving what many had believed impossible. Nevertheless, when the Tripos list was published, her name (and that of the other 16 women) still appeared below that of all the men.[4]

Between 1890 and 1909, the last year in which there was an official order of merit, around 20 or so women sat the examination each year. After the change in regulations the number of both women and men fell, with the number of men falling even more during the war period, especially once conscription began to bite, as evidenced below in Appendix One. Nevertheless, as the century progressed, the number of women completing the Mathematical Tripos course each year generated an increasing pool of mathematical talent, talent that could be utilized for the war effort. Not only were these women highly trained mathematically but by succeeding in the Mathematical Tripos they had proved themselves hard workers under pressure, an essential quality in a time of crisis.

The first woman's university college in the United Kingdom was Bedford College, which was founded as a higher education college for women in 1849 by Elizabeth Jesser Reid, and it became part of the University of London in 1900. During the War, the number of women in teaching roles at the College increased dramatically, notably in the chemistry department, which was requisitioned by the government to conduct research for the military on gas warfare. Chemistry was another area of academic and practical expertise in high demand for application to aeronautics, primarily in the specialization of materials science. The integrity and efficacy of aircraft construction hardware was a salient factor in the success or otherwise of new designs. Bedford thus educated a number of women who would make significant contributions to the war effort. They were not all thoroughbred mathematicians, but they certainly required, and would have doubtless received, a solid grounding in mathematics to underpin their respective work in physics, chemistry, and engineering.

Another academic institution that produced suitable female candidates for employment in the field of aeronautics was East London College, which was born during the latter part of the 19th century out of the People's Palace, a philanthropic organization designed to bring culture, recreation and education to the East End of London. Funded by the Beaumont Trust and the Drapers' Company, one of the Livery Guilds of the City of London, The People's Palace established Technical Schools to train a new generation of tradespeople, but it soon became obvious that there was a need for higher education opportunities in this area of the capital. Teaching was expanded to include the sciences, arts, and humanities, and the Schools were formerly admitted into the University of London in 1915 under the new name East London College (ELC). The College itself became a centre for teaching and research in the subject of aeronautics and, in the 1930s, became Queen Mary College.

Royal Holloway College would also provide many suitably qualified women to feed the growing demand for mathematics-based technical expertise. Holloway was founded as a women-only institution. Funded by entrepreneur Thomas Holloway, the College officially opened the doors to its spectacular Founder's Building in 1886, with the first students arriving the following year. Like Bedford, the College became a constituent part of the University of London in 1900.[5]

A better understanding of the nature of the work being undertaken by women mathematicians and scientists during the cataclysm of WW1 can be gained by considering a selection of individual case studies of some of those employed at the Admiralty, NPL, RAF and UCL. Whilst not exhaustive, these few examples cast light on the nature and variability of these women's backgrounds, education, and pathways into the realms of aeronautics and anti-aircraft gunnery. They also illustrate their diverse journeys and interests beyond the war.

The Admiralty Air Department

In 1917, as the air war raged in Europe and involved ever-increasing numbers of aircraft and aircrew, the need to ensure the structural integrity of existing and new aircraft designs became paramount. In London, Wing Commander Alec Ogilvie led the Technical Section of the Admiralty Air Department, which included a number of individuals dedicated to addressing aircraft structural issues; among them were a number of women mathematicians. A photograph held in the archive of Annie Trout, who was a member of the team, offers an intriguing insight into the number of women being employed in the Department at the time and reveals their identities. (Figure 1)[6] They were an eclectic group, but all shared the common goal of wanting to apply their academic groundings in mathematics and science to contribute to the structural integrity and safety of RFC aircraft and aircrew.

At least three of the women shown in the photograph were educated at Royal Holloway: Olive Moger, Annie Trout, and Dorothy Chandler. Moger attended Bath High School as a teenager and was awarded a scholarship to study mathematics at

Holloway, graduating from London University in 1903 with a second-class honours degree. She then moved into the world of topography, working in London on the Victorian Histories of the Counties of England project,[7] and in 1917 was at the Wheat Commission working as a statistical clerk. As applies to a number of the women mentioned in this narrative, the exact nature of how she was recruited to work at the Admiralty is unclear. In Moger's case it is also difficult to determine with any certainty her precise role within the department, although her academic qualifications and previous employment imply she would likely have been working in some mathematical context. Following the War, however, her achievements are better documented. She became a genealogist renowned for her passion for the transcription and cataloguing of wills.

Annie Trout graduated in 1907 from the University of London with a first-class honours degree in mathematics. As was common for women holding such a qualification, she moved into education, cementing her credentials in 1908 with a certificate of efficiency in teaching from the University of Cambridge. Following the War she took up a post at the University of Southampton as a lecturer in mathematics. As evidenced by the material held in her archive at the University, Trout was a mathematician who engaged completely with the task in hand at the Admiralty. Her personal copy of the core text used to inform the Department's modus operandi, the *Handbook of Strength Calculations* (Pippard & Pritchard, 1918), is embellished with copious handwritten comments to elaborate and clarify various mathematical techniques. She also compiled her own set of detailed notes, complete with sketches and diagrams, covering a diverse range of technical material associated with aeronautics. There is also evidence of her excitement and pride in being part of the rather exclusive group at the Admiralty. Among her reminiscences of the period, she recalls a special show of captured German aircraft put on in the London Borough of Islington in 1918:

> The variety in structure was far in advance of our own, which had remained as far as wing structures were concerned very much the same in fundamentals as in 1914. One machine had markedly swept back wings with the depth diminishing towards the wing tip. This came to mind when I first saw a Delta wing. The show was very secret and confidential, but our own Section was allowed to see it!

Something else Trout reveals in her notes is that Ogilvie was happy to authorize flying experience excursions for anyone in the Stressing office who might be interested in taking to the air, although she gives no indication as to whether or not she took advantage of this rather tempting offer. Women were apparently viewed as being preferentially suited to some tasks over their male counterparts. Relating a test she attended of a new aircraft component that had been designed at the RAF, she notes: "One test I watched was of a new construction […] with many small rivets. I was told then that women were far better for this riveting than men." Hidden away in Trout's archive is a small postcard from someone who signs off, ''Salutations, H.P.H''. The content comprises the resolution of a problem in the field of Cremona transformations, hinting that the author has to be Trout's co-worker at the Admiralty, Hilda Hudson. The card is dated 26th October 1926, which tells us that the two women had remained in touch after the War and were clearly drawing upon each other's mathematical expertise to resolve conundrums. There are two remarkable photographs in the archive. One is Trout’s own immaculate copy of the departmental photograph from the Admiralty, and the other is an image from 1938 showing the attendees at a national conference held in Oxford for university lecturers in engineering and mathematics. Of the over one hundred delegates, the only woman present is Annie Trout, hinting at her rather unique status in academia at the time, and highlighting the lack of inter-war progress made in establishing women mathematicians in academic posts in higher education in Britain.

Dorothy Chandler was an undergraduate at Holloway from 1907 until 1910, graduating in mathematics with second-class honours having first studied for the Intermediate Arts exam which covered Latin, English and Applied Mathematics. Chandler worked on aircraft design, and is known to have flown as a passenger in 1918 aboard one of the largest aircraft of the time, the Handley Page V/1500, sitting in the tail gunner’s cockpit, which must have been quite an experience for the office-based worker.

Cambridge University provided two of the key members of the group who appear in the Admiralty photograph, Hilda Hudson and Letitia Chitty, and another important contributor who is not shown, Beatrice Cave-Browne-Cave. Hudson was chef d'équipe to the other women. She arrived directly from a teaching post at West Ham Technical College, whilst Chitty came directly from university, interrupting her undergraduate studies. Beatrice Cave-Browne-Cave transferred directly from Karl Pearson’s laboratory at UCL under slightly acrimonious circumstances. It is worth considering the backgrounds and achievements of these women in more detail, since their stories exemplify the extent of the mathematical expertise they brought to the Admiralty.

Hilda Hudson was born into mathematics. Her father William lectured in mathematics at Cambridge and was subsequently appointed Professor of Mathematics at King's College, London, shortly after Hilda's birth in 1881. Her mother read mathematics at Newnham College, Cambridge, and her elder brother excelled at St John's, Cambridge, achieving the coveted accolade of Senior Wrangler in the Mathematical Tripos of 1898; her sister would, very creditably, be ranked alongside the equal-8th wranglers on the list of 1900. What pressure then on Hilda to shine when she arrived at Newnham in that same year. Like her family before, however, she rose to the challenge and held bragging rights over her sister by achieving a mark equivalent to the 7th wrangler on the list of 1903 following Part I of the Mathematical Tripos examinations. A year later she took Part II of the Tripos – the only woman to do so – and was placed in the third division of the First Class. After leaving Cambridge in the summer of 1904 she spent the winter semester at the University of Berlin where she attended lectures given by Hermann Amandus Schwarz, Friedrich Schottky, and Edmund Landau.[8] Her return from Germany saw her back at Cambridge, first as a lecturer and later as an Associate Research Fellow working on 'Birational Transformations in Three Dimensions', where she was looking to improve and develop work done previously by Arthur Cayley and Corrado Segre.

Perhaps a defining moment in Hudson's life came in 1912 when she became the first women to deliver a communication at the International Congress of Mathematicians (Hudson, 1912). A short spell in the United States at Bryn Mawr College working with Charlotte Scott preceded Hudson's appointment as a lecturer in mathematics at West Ham, which coincided with the advent of the Institute’s Junior Engineering School for Boys. Situated in the East End of London, the facility opened in 1900 to provide courses in Science, Engineering and Art for boys. Later, secretarial and trade courses for girls were added and eventually, in 1913, came the Junior Engineering School for Boys. It was the seedling of what has now grown into the University of East London. Hudson resigned from her research fellowship in Cambridge at the end of March 1913, two months before its formal conclusion, to facilitate the move to London.

The exact reason Hudson decided to leave her teaching post in 1917 and join the civil service is unclear, but the government had been actively running recruitment drives to draw women into the vacuum created in the traditionally male-dominated professions by conscription, which had been introduced for men in 1916. She was immediately drafted into the Admiralty to mentor the group of women that would become an essential cog in the wheel of the Stressing Section of the Structures office. She was slightly older and more experienced than most of her female colleagues and had the presence and work ethic to set a fine example, soon earning herself the title of Sub-section Director. She also demonstrated her mathematical flexibility, temporarily casting aside her passion for, and expertise in, geometry to enter the applied world of moments, stresses and strains. This transition should not be underplayed; these are disparate disciplines within mathematics. In addition to acting as the pivot between the key men in the department, Hudson would individually author two notable pieces of work that were published after the War. The first article, ‘The Strength of Laterally Loaded Struts’, appeared in *Aeronautical Engineering* in June of 1920 (Hudson, 1920a). Her second piece, ‘Incidence Wires’, appeared in the *Aeronautical Journal* in the same year (Hudson, 1920b).

Letitia Chitty, unlike Hudson, was not surrounded at home by a family of high-achieving mathematicians, although they were all academically minded, having a particular affiliation with Balliol College, Oxford. Having been schooled by private tutors at Winchester College,[9] she went up to Newnham, Cambridge, in 1916 to read mathematics. Her talent for the subject soon became apparent and, as the demand grew in London for competent mathematicians to assist with the war effort, it was agreed that she could be released from her undergraduate studies with the promise of a return once the conflict had ended. Rumours of Hudson’s work had already filtered back to Newnham via the dons’ network, so the Admiralty was where Chitty wanted to be. By a somewhat convoluted route, in August 1917, the now twenty-year-old Chitty presented herself for work in London. She was allocated a shared room with Chandler and Mary Hutchison.[10]

Some insight into the mathematics being used and mathematical methods being employed by the Stressing Section at that time can be gleaned from Chitty's later recollections of her time at the Admiralty.[11] “We relied upon our slide rules and arithmetic in the margins, supported by the theorem of 3 moments and Southwell's curves for struts”, she states, indicating the manual nature of calculations, and a reliance on the adaption and application of known mathematics to the novel situation an aircraft in flight presented.[12] The curves she mentions relate to the contemporary preference for mathematical equations to be offered in graphical form for ease of use. It is clear that Chitty was inspired by Section leader Sutton Pippard during her time at the Admiralty, and there was certainly an element of mutual respect. Such was Pippard's influence that, after the War, Chitty returned to Cambridge University and immediately transferred from mathematics to engineering, later being placed in the First Class in the Mechanical Sciences Tripos, the first woman ever to achieve this distinction. She would later team-up with Pippard to undertake stress analysis on all manner of objects, including arches, wheels, dams, and extensible cables. Pippard was placed in charge of the Civil Engineering Department at Imperial College in 1933 and was reunited with Chitty when she was appointed his Research Assistant in the following year. Then began a fruitful academic partnership, as witnessed by the many subsequent joint publications spanning the years 1936–1960 (Skempton, 1970). Prior to this symbiotic collaboration she also found occasion to work with in the field of hydrodynamic stability, emphasizing her remarkable flexibility.

Beatrice Cave-Browne-Cave was one of the first acquaintances made by Chitty upon the latter’s arrival in London. Cave-Browne-Cave was already working alongside the Holloway-educated mathematician, Eleanor Lang,[13] for Leonard Bairstow, who had himself recently moved to the Admiralty from the NPL. Bairstow was recognized as one of Britain’s leading aerodynamicists and become the first Zaharoff Professor of Aerodynamics at Imperial College following the War. These three academics formed a close partnership and would continue their association after the conflict, publishing two papers in the field of fluid dynamics.[14] Cave-Browne-Cave had been educated at home and, like Hudson, was surrounded by siblings who shared her passion for mathematics. She would eventually go up to Girton in 1895 and come away in 1899 having been placed in the Third Class in Part II of the Mathematics Tripos, perhaps, with hindsight, a rather modest reflection of her mathematical potential. She immediately took one of the few options open to female mathematicians at the time and became a teacher, taking a position at Clapham High School, but it would be an opening at UCL just before war began that would launch Cave-Browne-Cave's career in mathematics. Her sister Frances was employed as a lecturer of mathematics at Girton but had established a concurrent working relationship with statistician Karl Pearson at UCL, and so likely played some part in Beatrice's appointment. Beatrice's initial work was statistical in nature but, as the War intensified, and much to Pearson's chagrin, in 1916 she took an opportunity to earn more money by working at the Admiralty. In Pearson's view, she was "not playing the game" and had acted unfairly towards the laboratory.[15] At the Admiralty Beatrice worked on aircraft tail loading analysis and the study of aircraft oscillations, endeavour that resulted in a sole-authored paper that was published as an Advisory Committee for Aeronautics (ACA) *Technical Report* (Cave-Browne-Cave, 1918), and served to demonstrate her grasp of the relevant mathematics.

The National Physical Laboratory (NPL)

The NPL, located at Bushy House, Teddington, was established in 1900 to set standards in science and engineering. Various rumblings and statements of intent had been made at a number of the British Association for the Advancement of Science meetings during the 1890s as unease grew at Germany's advantage in this field, and so the arrival of the British equivalent of the Physikalisch-Technische Reichsanstalt, established in the mid-1880s, was long overdue. Initially the salient technical institutions and societies dictated the specializations at the Laboratory; mechanics and engineering, electricity, optics, chemistry, metrology, terrestrial magnetism, and thermometry were the chosen demarcations. The 19th century had witnessed the founding of a number of professional trades associations, the Institutions of Civil Engineers (1818), Mechanical Engineers (1847), and Electrical Engineers (1889) which were doubtless the most influential in determining the NPL's initial technical structure and focus. As time passed, however, its remit broadened and, in 1909, the Aeronautical Division appeared.

Two women who typified the throughput from Bedford College into the NPL were Dorothy Marshall and Marie Gayler. Marshall was born in London and educated at King Edward VI High School for Girls in Birmingham, which was founded in 1883, before enrolling at Bedford College in 1886. She later transferred to UCL, where she studied electrical technology, physics, and chemistry. She graduated in 1891 with a BSc and then remained at UCL until 1894 as a postgraduate research student. Her time was spent studying the effect of heat on liquids, and she published three papers in connection with this work, one co-authored with renowned chemist William Ramsey (Marshall & Ramsay, 1896). In 1896 she accepted a one-year Demonstratorship at Newnham College and then followed a career in education that took her to Clapham High School via Girton College, Avery Hill Training College, and Huddersfield Municipal High School. The demand generated by the War for skilled chemists drew Marshall to the NPL in 1916 where she was appointed as a Scientific Research Assistant. She remained at the Teddington facility for the balance of her working life, and published numerous papers in conjunction with Thomas Stanton, the Superintendent of the Engineering Department, that described the nature of fluid motion. A number of these joint papers were penned during the War, although not published until peace had been brokered. (Marshall & Stanton, 1920; Marshall, Stanton & Griffiths, 1921) Marshall and Stanton also teamed up with Oxford University physics graduate, Constance Jones, to do research into the properties of fluids in turbulent motion. Jones added essential expertise to the team's efforts to study the enigmatic properties of the boundary layer of such fluids with their bounding surface. Assisted by Jones, Marshall would eventually develop a new and extremely sensitive pitot device to improve the accuracy of data gathered in this pursuit, details of which appeared in an article in the *Proceedings of the Royal Society* in August 1920 (Stanton, Marshall, & Bryant, 1920); a technical drawing of the device can be seen in Figure 4. Part way through the war, Jones was moved out of the fluid dynamics laboratory into another department at the NPL concerned with testing and improving aerofoil design. It was during this period she collaborated with aerodynamicist L.W. Bryant and contributed to numerous technical reports relating to wing design.[16]

Marie Gayler was educated at St Mary's College school in Gerrards Cross, prior to Bedford, and was awarded a BSc. in 1912 that combined chemistry and mathematics. She then taught Science at Colston's Girls' School in Bristol until 1915 when she moved into her post at the NPL. Once there, she worked with Walter Rosenhain in the field of metallurgy. She was one of the first two women to be employed in the Metallurgy Department,[17] and made such an impression that she was kept on after the War to continue her work; she went on to have a full career at the NPL. Of great note was her work on the composition of amalgams used in dentistry.[18]

An alumna who typified the output from ELC was Isabel Hadfield, who graduated in 1914, a year later augmenting her degree with a Diploma of Education that she used to become a Chemistry Mistress with the Birmingham Education Council. In 1917 Hadfield was asked to join the staff of the NPL where she looked at chemical problems relating to the new field of aeronautics. Her main work focused on the type and treatment of fabrics used to cover the wings and fuselage of the aircraft. These materials had to be light enough so as not to degrade aircraft performance in flight, but sufficiently resilient to withstand the aerodynamic forces and weather to which they might be subjected. Hadfield was an important member of the Fabrics Research Coordinating Committee of the Department of Scientific and Industrial Research. Her post-war endeavor focused in the field of micro-analytical chemistry.[19]

The Royal Aircraft Factory

The Royal Aircraft Factory at Farnborough was the jewel in the crown of the ACA. The Factory went through something of an identity crisis during the immediate pre-war years; the Royal Balloon Factory, as it was known in 1909, became the Army Aircraft Factory in 1911 before completing its metamorphosis into the RAF in 1912. Its main purpose in its latter guise was to be a source of innovation in design in aeronautics and a primary research establishment, working in parallel with the NPL. The RAF was where new aircraft for the RFC were designed and tested, and also a centre of innovation and exploration in the field of aeronautics. During WW1 it witnessed the gathering together of some of the finest mathematicians, scientists, and engineers that Britain could muster, as the tactical advantage of controlling the air over a battlefield became apparent to the military hierarchy. The contributions of many of these academics were not confined to being made in the offices scattered across the RAF's real estate, some of them actually learned to fly so that they could conduct their own experiments in the air, whilst others volunteered as observers to amass in-flight data. Inevitably some of these brave individuals lost their lives in this pursuit of knowledge, but the impact they had on driving forward aeronautics in Britain during this period cannot be overstated.

It was into this cauldron of aeronautical progress and excellence that a number of women mathematicians and scientists were added as the War progressed. The RAF's central role in research and development at the time invoked rapid expansion and, coupled with the demand for men elsewhere, created a void that suitably qualified women were able to fill. Of the women who worked at the RAF during the war, one of the most mathematically talented was Lorna Swain, who had completed the Mathematical Tripos in 1913. Swain, the only woman wrangler of her year, had been coached by George Birtwhistle, a former Senior Wrangler, who himself had been prepared for Cambridge by hydrodynamicist Horace Lamb. Birtwhistle in turn instilled in Swain an interest in fluid motion and after the Tripos, prior to taking up a post at Newnham, she went on a research visit to Göttingen where Ludwig Prandtl had established a centre for the study of aerodynamics, and Felix Klein had been promoting German interest in applied mathematics. Swain's decision to go to Göttingen may well have been influenced by Arthur Berry, one of the mathematical lecturers who tutored at Newnham, who had studied with Klein in the 1880s; or it may have been the indirect influence of Lamb, via Birtwhistle, since Lamb and Klein were good friends.

With the outbreak of war Swain had to make a hasty departure from Germany, her visit having been cut short. To continue her research, she went to Manchester University to work with Lamb, who had been appointed to a chair there in 1885, and together they published an article on tidal motion. The following year she returned to

Newnham, but by 1917 she was to be found at Farnborough. There she worked on problems of propeller vibration and was another of the few women to have her name attached to one of the *Reports and Memoranda* of the ACA. The article in question, which appeared in 1919, was written together with Hanor A. Webb, another mathematician employed at the RAF (Webb & Swain, 1919).

After the War, Swain returned to Newnham and continued her research in fluid dynamics. This resulted in two papers, both published by the Royal Society. The first was on the motion of a viscous fluid, which she wrote jointly with Arthur Berry (Berry & Swain, 1923). Her work in this area linked closely to the work of Bairstow, Cave-Brown-Cave and Lang noted above. The second (Swain, 1929) was the result of a return visit to Göttingen in 1928–29 where she went to work with Prandtl at his Institute for Technical Physics, by then the world's leading establishment for the study of aerodynamics. In this paper she extended results of Prandtl's on the shape of the turbulent wake behind a body of revolution placed in a uniform stream, also including a discussion of the distribution of the velocity in the wake. It is a testament to the regard in which she was held by Prandtl that it was him who encouraged her to attack the problem and it was him who communicated her results to the Royal Society. Highly respected as a teacher and with a reputation for encouraging women to study mathematics, Swain had the distinction of being appointed a University Lecturer at Cambridge in 1926, one of the first women in Britain to hold such a position, lecturing regularly on hydromechanics and dynamics. (Kennedy, 1934)

Not all the women doing work for the RAF were located at the Farnborough facility. Ethel Elderton, for example, was based at UCL with Karl Pearson, where she had been since before the War. Elderton had attended Bedford College but on the death of her father had left early, without a degree, and became a schoolteacher. She did, however, have mathematics in her background. Her father and a younger brother were Cambridge wranglers and an elder brother was an actuary and a friend of Pearson’s, and it was her mathematical ability that in 1905 led to her employment at UCL where she worked in the Eugenics Laboratory of Francis Galton. According to Rosaleen Love, Elderton was the woman who did most to wear down “Galton's prejudice that women were intuitive unintellectual creatures incapable of sound academic work.” (Love, 1979, p. 152) And she certainly proved herself to be an extremely capable statistician, publishing a *Primer of Statistics* together with her elder brother in 1909, as well as many papers as a sole author and with Pearson both before and after the War.

Elderton produced an important joint paper with Pearson and another mathematician, Andrew Young, which considered torsion in the propellers being used by aircraft (Young, Elderton, & Pearson, 1918). The relevance of this research was that it related to the effect of the flexing force of the air on an aeroplane propeller rotating at high speed. Since the flexure of a beam of asymmetrical cross-section produces a significant torsion, there were serious implications regarding the efficiency and speed of a rotating propeller because of the changes to the angle of attack of the blade to the relative airflow that such torsion could produce. The team’s analysis concluded with a formula that could be applied to calculate the approximate torsion per unit length on a propeller due to the unbalanced shear-couple it experienced when rotating at high speed. The arguments offered to justify the formula involve some relatively complex mathematics, mostly based upon and developing original work by Saint-Venant,[20] but there is also a large element of numerical computation. It is not clear how the work involved in producing the paper was divided amongst the authors, but since she had a reputation as an energetic computer and much of her other work with Pearson concerned statistical analysis it is likely that she contributed substantially to the numerical work.

A woman mathematician actually based at Farnborough was Annie Betts. Graduating in 1906 with a BSc from London, Betts, who came from a family with an engineering background in railway construction, was also involved in the development of aircraft propellers, co-authoring a paper with H.A. Mettam that derived formulae for predicting certain aspects of aircraft performance (Betts & Mettam, 1918).[21] She took a keen interest in aeronautics beyond the War, combining this with her passion for apicology. Editing *Bee World* for many years, she would write no fewer than 170 articles for the publication.

High-angle range tables at University College London (UCL)

As well as working on aeronautics and helping to keep aircraft in flight stable, controllable and structurally sound, mathematicians were also engaged in what might be considered the converse: shooting aircraft down. World War One was the first conflict to be fought in the air in addition to land and sea, and at its outbreak the ballistics of anti-aircraft gunnery was a subject in its infancy. England had not been invaded since the Dutch fleet had sailed up the Thames in the 17th century but now there was the threat of invasion by air, and not only by German aircraft but, and terrifyingly, by Zeppelins. The situation is well-captured by a letter to Karl Pearson from Adelaide Davin, one of Pearson's statistical staff at UCL, written on 9 September 1915:[22]

> The whole of London is in a state of subdued excitement today as a result of the raid last night. We are all congratulating ourselves that we have seen a Zeppelin at last, although the N. Londoners had a much better view than the S. From all accounts the damage appears to have been greatest just at the back of College. A bomb fell in the centre of Queen's Square, and nearly every window is smashed – numerous shops were destroyed in Theobalds Road, and several houses in Red Lion Square have been seriously damaged. I was coming home in a tram just before 11 o'c. when the driver called out that there was a Zep, and that it had been fired at twice – then the tram was stopped, and the lights turned out, whereupon several women began to shriek. I got out and walked home, to find all the neighbours in the street gazing heavenwards. Nobody obeyed the Instructions to seek shelter. We could see the flashes from the anti-aircraft guns, but they all went very wide of the mark. …

To combat the threat, the Ministry of Munitions set up the Anti-Aircraft Experimental Section (AAES). At Whale Island near Portsmouth, mathematicians were deployed carrying out ballistics experiments and gathering data, while at UCL, Pearson and his human computers were converting that data into anti-aircraft graphic range tables for use by soldiers at the front. (Figure 3) It was complex and detailed work, far more complex than that required for flat fire which essentially involves shooting at a stationary target rather than one moving fast in the air.[23] Pearson had employed women in his two statistical laboratories before the War, so it was natural that he should continue to do after he had made himself and his laboratories available for the war effort.[24] Initially members of staff from the laboratories produced unemployment charts for the Board of Trade, calculated the torsional strain in the blades of aeroplane propellers for the RAF (as previously described), and calculated bomb trajectories for the Admiralty Air Department. But it was the work for the AAES during 1917 that occupied almost everyone in the laboratories and made the most substantial contribution in service of the State, and much of it was done by women. In January of that year, Pearson had two men on his staff and four women. By the end of the year the staff had increased in number to twenty, of whom nine were women, some doing draughtsmanship and others engaged in computing.

One of the most valued members of Pearson's staff during the war was Adelaide Davin, who had obtained a first-class degree in science at UCL in 1912 before beginning work with Pearson on statistical research connected with the evolution of mammals.[25] An able draughtswoman, a skill honed during her earlier biological work, she was responsible for the "most beautifully prepared" ballistics charts. These charts were not only praised by the mathematicians working in Portsmouth, but they were highly regarded by the British Expeditionary Force in France. (Barrow-Green, 2014) In November 1917, the Comptroller of the Ministry of Munitions wrote to Pearson to say that he very much appreciated Davin's "public spirited action" in remaining in his team "in spite of the fact that she could probably obtain a higher salary elsewhere."[26] When Pearson handed over the responsibility for the AAES work to the Ministry of Munitions in the spring of 1918, he wrote in his journal that, "The only member [of staff] who will be a serious loss is Miss Davin, who has been invaluable for the whole of our war work."[27] After the war Davin made a career in botany, being awarded a

PhD in 1928, and working for several years in Ireland. She returned to England to work as part of the team at the Norfolk Flax Establishment at Sandringham, which made an important contribution to the war effort in World War Two.

Another woman employed on AAES work was Ethel Elderton who moved into it at the beginning of 1917 along with the rest of Pearson's team. Her enthusiasm and capacity for hard work remained undimmed, and in the summer of 1917 Pearson singled her out, together with Davin, for additional pay for working extended hours and for giving up their customary 12-weeks holiday. She got on very well with Pearson, being the only member of his team to remain with him after the transfer of the AAES work to the Ministry of Munitions. The two of them continued working alone in the laboratory "finishing up one or two special gunnery problems." (Pearson E. , 1938, p. 92). Elderton remained at UCL for the rest of her career, being promoted to a readership in 1931. Writing in 1930, Pearson considered her employment at UCL to be 'a most happy choice'. (Pearson, 1930, p. 258)

Conclusion

Mathematics, particularly engineering mathematics, was not a field populated by many women in the early 1900s. There was little societal precedence, encouragement or support for it to be otherwise. The women discussed in this chapter, however, certainly stand out as clear examples of those who swam against the prevailing tide of prejudice and conventional expectation. Many of them benefited from familial stimuli and sound financial backing, traits that were almost obligatory prerequisites for any young woman aspiring to go up to a college such as Newnham or Girton. But infringing the male-dominated world of mathematics also demanded other intrinsic qualities. These women were eminently capable of original and independent mathematical thought and had the strength of character to overcome the tradition standing in their way. Their mathematical flexibility was also testament to their broad understanding of the subject. Many of these women were also groundbreakers, fine examples being Hudson, the first woman to deliver a paper at an ICM, Chitty, the first woman to be placed in the First Class in the Mechanical Science Tripos, and Cave-Browne-Cave, one of the few women to sole-author an ACA *Technical Report*.

Objectively, much of the mathematics and science being undertaken and addressed by these women whilst working for the Admiralty, RAF, NPL, or AAES during the war could not always be described as exceptional, but it was certainly necessary. With each new design of aircraft came the concomitant demand for the calculations that would determine its structural integrity and limitations. With each new range table came the need for greater accuracy. Without competent and dedicated mathematicians and scientists, the new breed of industrial aeronautical engineers would have been exposed to relying entirely on the rather blunt tools of judgement and experience. That said, whilst the bulk of the mathematics may have been well established, its specific application to aircraft or gunnery was not, and it was here where the challenges lay.

The pathway leading to a career in applied mathematics outside of education for female mathematicians at the start of the 20th century was strewn with all manner of obstacles, but the women discussed here were clearly able to negotiate them admirably. Did the demands and urgency of the war assist their career progressions?

The conflict certainly created employment opportunities as men were taken in ever-increasing numbers by conscription, but these women nevertheless seized their chance to infiltrate traditionally male-dominated domains. Their calculations, expertise and diligence will inevitably have prevented many unsafe aircraft designs moving from drawing board into production and provided information to make gunnery a more exact science; these were their practical legacies. However, these women represented more than just a technical check and balance in the chain of aircraft design and production, or efficient computers of range tables. They were pioneers who demonstrated that it was possible for women to overcome the dogmatic, institutionalized prejudices of the time, and they earned the right to stand tall as credible applied mathematicians during the First World War and beyond.

Table 1:

	Women Wranglers	**Women** Total including Wranglers	**Men** Wranglers	**Men** Total including Wranglers
1908	3	18	28	83
1909	1	10	31	74
1910	1	11	23	46
1911	1	12	24	52
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. .				
1914	2	10	25	58
1915	2	8	14	28
1916	2	12	11	20
1917	2	13	5	11
1918	0	7	3	4
1919	2	17	9	25

Numbers of men and women passing the Mathematical Tripos 1908–1919

Notes

[1] On 28 October 1915, The Times, in an article on 'The Demand for Qualified Women', reported that, "Already posts have been found in aircraft works where a Mathematics Tripos was of value". Two years later, on 31 August 1917, the same newspaper, in an article on 'Women's War Work', noted the "big demand" for women with degrees in mathematics.

[2] In order to win a high place in the order of merit, coaching was generally deemed essential. Among the most high profile of the mathematicians who supported women students was the Sadleirian professor, Arthur Cayley, who taught at Girton and for several years was chair of the Council of Newnham.

[3] 'Miss Fawcett's Honour: the sort of girl this Lady Senior Wrangler is', *The New York Times*, 8 June 1890, p.5. Scott later made her career in the United States as the inaugural professor of mathematics at Bryn Mawr College.

[4] After Fawcett's success, the clamour for women to be awarded degrees grew louder but still it was not loud enough. The University did not fully open its doors to women until December 1947. Those who wanted undergraduate degrees had to go to London or, from 1920, Oxford. Those who wanted higher degrees had to go abroad – the PhD did not come to Britain until after the First World War.

[5] From 1945 the College admitted male postgraduates, with the first male undergraduates arriving in 1965. Royal Holloway and Bedford Colleges merged in 1985 and became the single entity, Royal Holloway and Bedford New College.

[6] Photograph of The Admiralty Air Department, 1918, by kind permission of the Hartley Library, University of Southampton. MS112 Papers of Miss A.M. Trout LF 780 UNI 2/7/75.

[7] The Project began in 1899 and employed approximately 20 women to write the parish histories for the various counties of Britain.

[8] It is likely that Schwarz and his colleagues were major influences in developing Hudson's interest in conformal transformations, a topic initially introduced to her by mathematician Arthur Berry during her time at Cambridge, and one that would eventually dominate her mathematical research, which culminated in 1927 with the publication of her comprehensive and well-respected treatise, 'Cremona transformations in plane and space' (Hudson, 1927).

[9] Despite Winchester College being a school only for boys at the time, Chitty's access to tuition there would likely have been a boon derived from her father's position as archivist. Winchester College was one of the top private schools in the country and it is therefore likely that Chitty was tutored to a high standard in mathematics.

[10] Mary Hutchison was a product of the ELC, graduating in 1913 with a BSc Honours in Mathematics; she and Chandler both arrived at the Admiralty a week before Chitty.

[11] Chitty contributed to the centenary edition of The Royal Aeronautical Society's *Journal* in 1966 (Chitty, 1966), an article from which all the quotes used above are taken.

[12] The 3 moments theorem here refers to Émile Clapeyron's work in the middle part of the 19th century, which addresses the relationship between the bending moments at three consecutive supports of a horizontal beam (Clapeyron, 1858).

[13] Lang, a student at Royal Holloway, obtained a third-class honours degree in mathematics in 1905, and went on to be awarded an MA from UCL in 1911.

[14] (Bairstow, Cave, & Lang, 1922) and (Bairstow, Cave, & Lang, 1923).

[15] Pearson's *Journal of the Galton Laboratory 1915-1918*. Pearson Papers, UCL Pearson 4/17, p.101.

[16] Jones co-authored numerous Reports and Memoranda (R&M) at the NPL, including R&Ms 355, 366, 375, and 418. She and her colleague L.W. Bryant married during their time at the NPL, her name appearing as C.N. Bryant in subsequently published work.

[17] The other was Isabel Hadfield.

[18] She was awarded an MSc in 1921, and a DSc in 1924, both from Bedford, along with MISI/MIM Hon MBDA as her career progressed.

[19] A comprehensive account of the role of British women chemists during WW1, including Isabel Hadfield, can be found in (Rayner-Canham & Rayner-Canham, 2008).

[20] Adhémar Jean Claude Barré de Saint-Venant (1797-1886) was a French mathematician and mechanician who worked in the fields of stress analysis and hydrodynamics.

[21] Mettam was a Cambridge mathematician who was a member of the post war Cambridge Aeronautical Club. Newnham and Girton Colleges were allowed to be members of the Club and, given her experience in aeronautics, Letitia Chitty was elected onto the Club's Committee.

[22] A. Davin to K. Pearson, 9 September 1915 [Pearson Papers, UCL, 674/9].

[23] Each table supplied the ballistic and fuze data for a gun (with a given muzzle velocity) in graphical form. The fuze time scale is arbitrary (i.e. not in seconds). Usually, as in the range table shown in Figure 3, the maximum setting was 22, which represented something between 40 and 60 seconds, depending on the type of fuze. The horizontal range and height are the *x*- and *y*-axes, and the curves plotted represent actual trajectories for different elevations of the gun.

[24] For example, in 1908, five out of fourteen research workers in the laboratories were women, and Pearson wrote to Galton that, "their work is equal at the very least to that of the men. They are women who in many cases have taken higher academic honours than the men and are intellectually their peers. They were a little tried therefore when your name appeared on the Committee of the Anti-Suffrage Society!" - quoted in (Love, 1979, p.146). It should be noted, however, that at this time women were paid considerably less than men, which might well have been a factor.

[25] After the war, Davin published papers with Pearson. We are very grateful to Adelaide Davin's great niece, Alison Pearson (no relation to Karl Pearson) for supplying us with information about her great aunt's education and later life.

[26] A.E. Moore to Karl Pearson, 16 November 1917 [Pearson Papers, UCL, Pearson 9/8/1].

[27] Pearson's *Journal of the Galton Laboratory 1915-1918* [Pearson Papers, UCL Pearson 4/17, p.108].

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