Now the dust has settled: A view of Robert Hooke post-2003

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5 November 2008

The installation of a memorial to Robert Hooke in St Paul's Cathedral next month is the latest act in an outburst of activity surrounding the tercentenary of his death in 2003. Hooke's hectic life and work were subjected to intense scrutiny: biographies, essays and academic papers were published; lectures were given; items appeared in the press and on radio and TV; conferences were held in Oxford and at The Royal Society in London; celebratory dinners were enjoyed; a Hooke portrait competition was held; organised visits were made to places where he lived; exhibitions were mounted; a play was commissioned and performed; and memorials were installed.[i] Now that the dust raised by these activities has settled it is time to offer an assessment of what they have revealed about Hooke that was not clear before.

In the two decades preceding the tercentenary, the relationship between Hooke's social position and his scientific authority was an issue. Hooke did not fit easily into any one of the social groups in 17th-century England. This led to the view that lacking the private income of a Gentleman, he was dependent on others for his living; as a consequence his authority in science was compromised by his servile social position, uncertain moral values and the character of a tradesman.[ii] Many recent publications present evidence contrary to this view either implicitly or explicitly. They have also justified Hooke's complaint that he had been betrayed by some members of the Royal Society.[iii] He was cantankerous, but often for understandable reasons. By concentrating on what he did, rather than on who he was, people with expertise in engineering, architecture, physics, mathematics, school-teaching, land surveying and psychology have revealed new aspects of Hooke's busy life and work.

Baconian Experimental Philosophy in Practice

When Hooke was appointed as the Royal Society's first Curator of Experiments in 1662, he became the first professional experimental natural philosopher - or as we now say - experimental scientist. He set out his intentions in the Preface to Micrographia, published in 1665: to act in accordance with the three Baconian principles of observation, rational debate and record in order to assist and improve the natural world to the benefit of Mankind. To achieve his ambition, Hooke intended to compensate for man's imperfections by rectifying defects in sense, memory and reason. He had the manual skills of a first-class mechanic, but he also possessed the enquiring and rational mind of a philosopher and a determination to improve the daily lives of his fellow citizens. With such an unusual combination of attributes he became mainstay of The Royal Society in its early days and an influential figure in the rebuilding of London after the Great Fire of 1666.

Intellectually Hooke was ahead of his time. His theory of memory 'rests in glorious isolation as a one-off piece of proto-psychological theorizing of a kind for which the intellectual climate was quite unripe'.[iv] He had other ideas that went against contemporary thought: he understood memory as an organ, susceptible to physical correction in the same way as the senses are capable of improvement in pursuit of knowledge of the natural world.[v] He also had perceptive ideas on geological change and the evolution of species, based in part on what he had seen in the cliffs of the Isle of Wight where he lived as a child.[vi]

Hooke was supreme at observation. He used all his senses to generate evidence with which he then engaged both physically and mentally in order to increase his understanding of the particular natural phenomenon he was investigating. Two examples from Micrographia illustrate his engagement with experimental science. When he looked through his microscope at a stinging nettle, he saw 'sharp needles' which he found 'by many tryals' to be 'hollow from top to bottom' [1]. Is it these which 'sting?' To find out, he rigged-up a simple magnifying glass in a frame which he wore like a pair of spectacles so that he could more easily see and manipulate the nettle. As he thrust one of the needles into his skin he felt a burning sensation as the needle, remaining rigid, depressed a small bag at its base which caused a fluid to flow upwards through the hollow needle as if in a siphon. He concluded that the pain was caused by the liquid, not by the point of the needle. He then wrote more than four pages of text, speculating on why the pain eventually goes away and citing many similar phenomena observed by Christopher Wren.

His big telescopes enabled him to make 'the greatest contribution to observational astronomy since Galileo'.[vii] He was able to see the moon's surface in much more detail than anyone else, but he was not satisfied with that achievement [2]. He wanted to understand why the moon looked the way it did: 'a very spacious Vale, incompassed with a range of hills'. Perhaps heavy objects had fallen on the surface; or perhaps an event from below the surface, similar to an earthquake or a volcanic eruption, was the cause. Hooke decided to carry out some experiments to help him decide.

He filled a tray with a mixture of pipe-clay and water. By dropping heavy weights onto the surface he saw that they created shapes very similar to those on the moon. But he rejected falling bodies as the cause of moon craters 'for it would be difficult to imagine whence those bodies should come'. His second experiment was to boil powdered alabaster in a pot. When he removed the pot from the fire he noticed that where bubbles had arisen, shapes similar to moon craters appeared on the surface of the cooling alabaster. When he closed the shutters across the windows in his room and shone a light onto the surface of the alabaster he saw that it does 'exactly represent all the Phaenomena of these pits in the Moon, according as they are more or less inlightened by the Sun'. He then set out several reasons why moon craters could have been caused by some internal interaction between vapours and the material from which the moon is made under the influence of great heat, as occurs on earth. He therefore preferred this explanation to his earlier hypothesis.

There are many instances of Hooke using all his five senses in his experiments. His boy-chorister's ear enabled him to estimate the frequency of an insect's beating wings by comparing the pitch of the sound they made with the sounds of vibrating strings of musical instruments. He used taste and smell and touch as part of his sometimes painful investigations into the medicinal properties of a great variety of substances. Unfortunately, engaging his mind and body in these investigations led to something more than scientific understanding. A sufferer from chronic ill-health, he responded too enthusiastically to the urging of the physicians in The Royal Society to experiment on himself with new substances and record their effects on his bodily functions. He took measured doses of anything that he thought might alleviate the noises in his head, dizziness, nausea and headaches. His experimental self-dosing was a factor that contributed to his slow decline and death.[viii]

The general corporeality of his experiments fuelled his imagination and inspired him to find intuitive answers to many questions about the natural world that were in his mind. He was convinced that orbital motion was made up of a combination of motion along the tangent and motion towards the centre by sensing with his muscles the different forces required to set a long pendulum with a heavy bob into different motions. At a lathe he could feel, see, smell and hear the effects of shaping an irregular and inhomogeneous material into a component he had designed for a particular instrument. When grinding a lens, or polishing a speculum through the night, he could feel and see how effective his efforts were at removing small surface irregularities. His practical skill gave him an intuitive insight into the properties of materials. Very few of his colleagues in the Royal Society had, or thought it necessary to acquire, such skills.

Hooke published drawings and written instructions for making particular instruments. He described in detail how he had used his instruments in experiments, recorded the outcomes and set out his conclusions. His intention was to allow others to do their own experiments, draw their own conclusions and see whether or not they agreed with his. Relatively few of the hundreds of people who have written about Hooke as a figure in the history of science have sought insights into his work by making his instruments and repeating his experiments.[ix] This omission has recently been rectified in a few cases. The scientific value of Hooke's work has been assessed by repeating and elaborating upon some of his less spectacular but more difficult experiments. As a result, some important conclusions have been drawn about the contemporary consequences of giving a lower status to technology than to 'pure' science.[x] A similar dichotomy is identified in a different context where Hooke's 'materiality and manipulation' is compared with Newton's more abstract work. Ingenuity had moral value insofar as it was associated with 'ingenuous', indicating simplicity and transparency.[xi]

Hooke's ingenuity was fully expressed in his equatorial quadrant. Although mechanically complex, it was intended to make difficult measurements simple for anyone interested enough to use it. Horology, time-keeping and optics were combined so that one person could measure angles between stars as they moved across the night sky [3]. The instrument was probably never made: its key components were generally thought to have been unworkable in principle. When the components were made and tested recently they were found to perform in the way Hooke intended. He 'foresaw all the requirements of the classic clock-driven equatorial mounting for astronomical telescopes in 1679, but two centuries had to pass before the technology existed to put his ideas into practice'.[xii]

The Hooke/Newton Dispute

During the celebrations of Hooke's tercentenary, the media homed in on the notorious dispute about priority in understanding the mechanics of the relationship between gravitational attraction and planetary orbits. Evidence that Newton had plagiarized Hooke's 'discovery' would have been news. Fortunately, nobody in front of a microphone or a camera gave an opportunity for a strap-line on a front page or a sentence for the bongs at the start of ITV news. Newton rightly remains the supreme mathematical physicist; his mechanical model of the universe was the foundation of science and engineering for about 200 years, but it is very hard to accept his denial that he knew about Hooke's substantial understanding of planetary orbits and gravity. Hooke's name was inPrincipia, but only among the names of others said to have been wrong about planetary motion.

Hooke had convinced himself in 1666 that planetary motion was a combination of motion along a straight line tangential to the orbit, and motion towards the sun. In 1674 he published his concept of universal gravitation. But he knew that 'being convinced' was not enough for his idea to be generally accepted; either experimental evidence or a mathematical demonstration was necessary. Hooke, Wren and Halley knew that their mathematical abilities were inadequate to deal with planetary motion where the velocity varies along the elliptical orbit. Only Newton in England had the mathematical ability to find the law of gravitational attraction which accounted for planetary motion. In 1679 when Hooke was Secretary of the Royal Society, he wrote to Newton inviting him to consider a mathematical demonstration based on the ideas that Hooke had published earlier. The following year, in another letter to Newton, Hooke added that he had concluded gravitational attraction followed an inverse square law (in 1682 he published that he had reached this conclusion by analogy with light and sound). By 1680 Hooke had made known all his ideas on the nature of planetary motion and gravitational attraction to Newton.

When Newton published his mathematical explanation of planetary motion (and much else besides) in Principia in 1687, Hooke was very upset to find that it contained no acknowledgement of his ideas. A recent comprehensive review of the dispute has clarified many matters that have been argued over for decades. The review includes a report on a recent experiment which confirms that Hooke's interpretation in dynamical terms of a sketch by Newton was correct. It has also unravelled the complexities of a diagram constructed by Hooke in 1685. The diagram shows that if linear motion of a body is combined with motion towards a centre under a force proportional to the distance form the centre, the body will move in an elliptical orbit. This is a mathematical demonstration by geometry of orbital motion.[xiii]

Scientific Measurements

Measurements were the foundation of the discovery of Boyle's Law (first published in 1660) and were essential in the rebuilding of London after the Great Fire in 1666. Hooke was a key figure in these very different activities, but until recently his contributions to them have not been examined and compared.[xiv] Boyle's famous air-pump was designed by Hooke and made under his supervision by mechanics skilled in metalwork and glass-blowing [4]. The air-pump was used and maintained by Hooke throughout the experiments in Boyle's private laboratory in Oxford from 1658-1659. Contrary to popular opinion, the air pump was not used for the measurements that gave rise to Boyle's Law ('the volume of air is inversely proportional to its pressure'). When the law was first published by Boyle in 1660, the measurements which had led to it were not included and the book was attacked by Francis Linus. Boyle retaliated two years later by publishing details of the measurements in A Defence ... Against the Objections of Franciscus Linus ...

The device used by Boyle and Hooke can be seen at the edge of a plate inMicrographia. It was a glass tube in the form of the letter 'J'. The shorter limb, closed at the top, was only about a foot long. The other limb, open at the top, was about eight feet long [5]. The tube stood upright in the stairwell of Boyle's laboratory. Mercury was added in stages at the open end, compressing the air in the much shorter, closed, end [6]. Graduated paper strips pasted to the limbs served to record the levels of mercury in the tube. Pairs of measurements of the levels of mercury in the two limbs were published in the form of a table; the volume of trapped air was related to the mercury level in the smaller limb, and the pressure on it was related to the mercury level in the longer limb. The inclusion in the table of an additional set of theoretical values made the publication highly significant in experimental science. The theoretical values represented what the pressure readings should have been if the law were true [7]. Boyle and Hooke attributed the discrepancies between the theoretical and measured values to small imperfections in measuring with the human eye. Linus and any other critics could examine the discrepancies and judge for themselves whether or not to accept the law. If necessary, they could carry out independent experiments themselves before deciding.

A recent statistical analysis of the discrepancies between the theoretical and measured values has shown that Boyle and Hooke measured the mercury levels to ±1.6 mm.[xv] This very high precision is surprising, even though magnifying glasses were used and great pains were taken to avoid errors in reading and blunders in procedure. It is probable that the experiments were repeated many times and average values published. As a defence against criticism, the form of publication of the measurements could hardly have been bettered. Perhaps Hooke's tendency to engage in scientific controversy convinced the less aggressive Boyle that such a distinctive response to Linus was necessary. The word of the Gentleman Boyle was not enough, at least for Linus.

Hooke strove for many years to justify his understanding of gravity and motion by experiment and measurement, but failed to do so. He tried weighing heavy bodies at different heights and timing them as they fell freely under gravity. He made a portable differential gravimeter based on a weight suspended from a cantilever: the greater the force of gravity, the greater the bending of the cantilever, but all these attempts failed [8]. The first successful experimental verification of the inverse square law of gravitational attraction took place more than three centuries later in 1990 when Hooke's idea of timing a falling body was used at a 300m-high meteorological tower near Erie, Colorado.[xvi] The published report (by nine authors) shows measured values together with the values to be expected under the inverse-square law, in exactly the same way as Boyle and Hooke published their results on the elasticity of air in 1662. The only difference in the form of the two sets of results is that the later table included a statistical analysis. Both experiments are examples of the essential cooperative element in scientific experimentation.

Civic Measurements

On 26th October 1666 the Court of Common Council of the City of London appointed Hooke as one of their three Surveyors to work with the King's three Commissioners of New Buildings to oversee the rebuilding work after the Great Fire. Of these six appointees, two were surprising choices: Wren as a Commissioner and Hooke as a Surveyor. Compared with their respective colleagues, neither could be seen to have had the requisite experience, but it turned out that their appointments were inspired. Both men were recognised at Court and in the City as clever, practical and trustworthy scientific colleagues who could be expected to cooperate effectively in the enormous task that lay ahead: the rapid restoration of the social and economic life of London. The idea for a grand new city desired by the King and by the City was soon abandoned as impossible to realise. Compulsory purchase of land for building wide new streets, boulevards and panoramic views along the Thames would have been prohibitively expensive, time-consuming and unacceptable to the citizens. Instead, London was rebuilt in only 8 years, mainly on the old foundations, but using brick and stone in place of timber. The new city was a much healthier place to live than the mediaeval city it replaced.

Hooke's contribution as Surveyor was unsurpassed. We are here concerned with his measurements, but they took place in a social and legal context which he did much to shape. He represented the City in drafting the rebuilding regulations for Parliament. Although three City Surveyors were appointed, resignations and illnesses meant that Hooke was the only one who worked throughout the period of rebuilding. As a consequence he took on about half the work that was intended to be done by three City Surveyors.

He had not served any apprenticeships and was therefore not a member of any of the Livery Companies to which the other City Surveyors had been admitted. His abilities were already well-known to the rulers of the City who had appointed him Gresham Professor of Geometry alongside scholars from Oxford and Cambridge Universities. His layout plan for a new city had impressed the Lord Mayor and Aldermen so much that they preferred it to the one put forward by their own Surveyor at the time, Peter Mills. Throughout Hooke's work as City Surveyor, his authority, leadership and integrity were unquestioned by the other City Surveyors, the citizens, and the City's rulers.

Hooke arbitrated in 550 building disputes between neighbours; he laid out more than 1,500 foundations for private rebuilding; and he certified more than 300 areas of ground lost through widening the streets.[xvii] We do not know how he carried out his measurements, but there are clues from the way he recorded and used them to calculate areas of lost ground. He measured only lengths, recording them in feet and inches, and often used convenient duodecimal arithmetic to calculate the area (if compensation were paid at x shillings per square foot, then compensation for each1/12th square foot would be x pence). Hooke always made fewer measurements than the minimum necessary to calculate the exact area of an irregular four-sided piece of ground. Instead, he used approximate methods for calculating areas. He knew of course that most of the areas he calculated were wrong, but he also knew that the errors were small and that a calculated area was never smaller than the true area. Hooke's renowned mechanical ingenuity has been attacked recently because he did not devise a new instrument for measuring London more accurately. No such instrument was necessary. Simple tapes and rods for measuring lengths were both quick to use, easy to carry about the city and accurate enough. Hooke knew that the citizens expected speed and fairness, not high accuracy. However, when an accurate map was needed, Hooke changed traditional practices in order to meet those expectations.

The Lord Mayor and Aldermen wanted an accurate plan of the rebuilt City as an administrative aid, so they asked Hooke to oversee the technicalities of the work. The plan at a scale of 1/1,200 (1 foot to 1 inch) was published in January 1677. It bore the title ... Actually Surveyed and Delineated, By John Ogilby Esq; His Majesty's Cosmographer. This is not entirely true. Ogilby, and his successor William Morgan, received funds from the City to pay for the plan, but the surveying and plotting were done by a team of land surveyors and the plates were engraved from the surveyors' plots by Wenceslaus Hollar. Hooke's role in all stages of the project can be glimpsed from the City archives and from his diary. Frequent meetings in coffee-houses took place between Hooke, Ogilby, Hollar and the land surveyor William Leybourne when the map-making was in progress. Hooke corrected Leybourne's errors, decided on the best way of covering the city with a regular array of 20 map-sheets, suggested cartographic symbols to Ogilby, vetted the trial prints from Hollar's plates and advised the City on how they should respond to Ogilby's pleas for more funds. Hooke was in overall control of the project; it was part of his role as City Surveyor.

Land surveyors at that time were usually engaged by private clients to survey country estates and produce relatively small-scale plans showing details such as buildings, tracks, woodland, field boundaries and areas. They now had to adopt quite different procedures and attitudes in order to survey a city at a large scale. The accuracy had to be significantly higher than for an estate survey (at a scale of 1/1200 a distance of a foot or two on the ground is visible on the plan) and they had to work as a team, not as sole independent practitioners with assistants. The city was divided up into blocks which were allocated to the individual surveyors[9]. Measurements within a block had to be self-checking [10], but each block had to match the surrounding blocks when plotted and fitted together.[xviii] Errors are inevitable in land surveying and generally should be insignificant, but if an error is large enough (visible when plotted at 1/1200 scale in this case) it is necessary to recognise it, find the cause and correct it. When blocks did not fit together, who was at fault? A surveyor's pride, experience and bluff no longer carried weight in a dispute.[xix] Teamwork was alien to them, but Hooke's status in the City ensured that the surveyors accepted what was a major change in the way they worked and saw themselves. Cooperation in measurement was, of course, an essential part of Hooke's Baconian science. He needed something similar now, and succeeded in getting it.

The outcome was a true-to-scale plan view of the city showing buildings of different types, parish and ward boundaries and a grid reference for locating specific places, streets and lanes named in a gazetteer [11]. It was the world's first 'A to Z' and has recently been found to be surprisingly accurate.[xx] However, it was not used for long as an administrative document because as the infrastructure of London changed, it became too difficult to keep the plan up-to-date.

Architecture

Between 1671 and 1693 Wren authorised a total of £2,820 to be paid as salary to Hooke from the fund for rebuilding London's parish churches. This was a large sum (about half the total cost of rebuilding a major church) but Hooke worked hard for it. Wren and Hooke had to find a new way of organising such a massive building programme. They moved away from the traditional construction procedures organized by a master-craftsmen and towards a modern architectural partnership.[xxi] Wren and Hooke decided on the design of churches and drew up technical specifications. Unit rates were then negotiated with selected contractors. Work in progress was supervised and the quality of the workmanship was monitored. Quantities of materials used in the construction were measured and their quality assessed. A contractor was paid only if the work satisfied the 'Wren and Hooke Partnership'. Wren was the senior partner in the design office, but Hooke supervised and assessed the work by visiting sites as he went about the streets of London in the mornings in his role as City Surveyor.

Hooke alone almost certainly designed some of the city churches: St Benet's Pauls Wharf and St Edmund the King and Martyr in Lombard Street are two examples that have survived. European influences on Hooke's architecture have been detected.[xxii] He designed and supervised the construction of various buildings, including the theatre of the College of Physicians in Warwick Lane (destroyed) the Monument (with Wren, intended also to be a zenith telescope for detecting the earth's annual motion around the sun) Bedlam Hospital in Moorfields (destroyed) Montague House (destroyed, formerly on the site of today's British Museum) and a church at Willen for Richard Busby, his Head Master at Westminster School. A wide-ranging examination of the science and architecture of Wren, Hooke and Perrault has revealed that Hooke had a variety of talents, including one as a 'Mr Fixit', which is exactly what the citizens of London needed at the time.[xxiii]

Conclusions

Hooke was known throughout all sections of 17th-century London society, from the Court to the urchins in the streets, not so much through his writings, but through his deeds. Non-historians as well as historians have clarified the great extent and variety of his work and given insights into what he did, and why. It was surprising to discover that literally hundreds of his manuscripts in the archives of the City of London had not been systematically examined and written about since they were deposited there more than 300 years ago. When they were unfolded, fine grains of sand sometimes fell out - an occurrence which led to the title of this lecture. It is equally surprising that so few people have repeated what Hooke did in order to try to understand him, despite his explicit descriptions of how he carried out his experiments. [xxiv]

We now know more of Hooke's formative years as a schoolboy and how he benefited from the unconventional educational views of his Head Master at Westminster School, Dr Richard Busby.[xxv] Near the end of his life, despite the shock of Principia and increasing melancholia brought about by his deteriorating health and the death of his niece Grace, Hooke continued to give his lectures, attend meetings of the Royal Society, walk through city streets, buy books and new spectacles, go into coffee-houses and gossip over tea in the home one of his former housemaids.[xxvi] He was buried in his parish church of St Helen's Bishopsgate, but his remains were disinterred along with those of several hundred fellow parishioners and re-buried in 1892 in a mass grave at Wanstead [12].[xxvii] When that became known, media interest in the idea of finding his skull and re-constructing his features vanished.

So we still can not see Hooke's face very clearly and in the absence of a published scholarly edition of his collected works we still do not know as much about him as we should. Some of his late metaphysical speculations deserve careful examination. He was a man uncomfortable in his time, socially and intellectually. His heavy workload and eagerness to take on even more prevented him from publishing enough of his scientific work. Yet his record-keeping for the City was exemplary: when a citizen came to him and asked for a duplicate certificate for lost ground, Hooke went to his field-books, found the relevant ten-year-old measurements among the hundreds he had made, recalulated the area and wrote a new certificate.

His belief that scientific knowledge allied with the skilled use of technology could improve the well-being of his fellow citizens was a major influence on the form and appearance of the new city. He studied the nature of air and light and ensured they entered the new streets and buildings of London. Despite our efforts, we have found no evidence that he was anything other than scrupulously fair in his dealings with the citizens of London at a time when many wealthy men were eager for preference. We can say with confidence that Hooke's civic virtue was what one would expect from a Gentleman.

References

[i]. At least 7 books on Hooke were published in England in the years 2002-2006: The Man Who Knew Too Much (Stephen Inwood, Macmillan 2002); London's Leonardo (Jim Bennett, Michael Cooper, Michael Hunter and Lisa Jardine, Oxford University Press 2003); The Curious Life of Robert Hooke (Lisa Jardine, HarperCollins 2003); A More Beautiful City(Michael Cooper, Sutton 2003, reprinted as Robert Hooke and the Rebuilding of London, Sutton 2006); Robert Hooke and the English Renaissance (edited by Paul Kent and Allan Chapman, Gracewing 2005);England's Leonardo (Allan Chapman, Institute of Physics, 2005); andRobert Hooke Tercentennial Studies (edited by Michael Cooper & Michael Hunter, Ashgate 2006). Memorials in Westminster Abbey, in the pavement at the foot of the Monument and in St Paul's Cathedral have been installed since 2003.

[ii]. See for example 'Who was Robert Hooke?' by Steven Shapin inRobert Hooke New Studies edited by Hunter & Schaffer, Boydell 1989, pp. 253-285 and A Social History of Truth also by Shapin, Chicago University Press 1994.

[iii]. See note 1 (above) especially the contentiously titled 'Robert Hooke: Gentleman of Science' by Mordechai Feingold in Robert Hooke Tercentennial Studies, edited by Cooper & Hunter, Ashgate 2006, pp. 203-217; 'Robert Hooke: a reputation restored' by Lisa Jardine ibid. pp. 247-258; and 'The return of the Hooke folio' by Robyn Adams and Lisa Jardine, Notes and Records of the Royal Society 60 pp. 235-239 (2006).

[iv]. Graham Richards, cited in'Hooke on memory and the memory of Hooke' by Douwe Draaisma in Robert Hooke Tercentennial Studies, edited by Cooper & Hunter, Ashgate 2006, pp. 111-121.

[v]. 'Graphic Technologies' by Nick Wilding in Robert Hooke Tercentennial Studies, edited by Cooper & Hunter, Ashgate 2006, pp. 123-134.

[vi]. 'The terraqueous globe and a theory of evolution' by Ellen Tan Drake in Robert Hooke Tercentennial Studies, edited by Cooper & Hunter, Ashgate 2006, pp. 135-149.

[vii]. 'Robert Hooke as an astronomer ...' by Hideto Nakajima inRobert Hooke Tercentennial Studies, edited by Cooper & Hunter, Ashgate 2006, pp. 49-62.

[viii]. See Lisa Jardine's The Curious Life of Robert Hooke, HarperCollins 2003, especially Chapter 6, for details of Hooke's self-dosing.

[ix]. One recent exception, notable for being commercial rather than academic, is a kit for making a scaled-down version of Hooke's microscope, complete with specimens to examine and draw. It is published by Gakken of Japan as vol. 5 in their Science for Adults series.

[x]. 'Assessment of the scientific value of Hooke's work' by S. H. Joseph in Robert Hooke Tercentennial Studies, edited by Cooper & Hunter, Ashgate 2006, pp. 89-108.

[xi]. 'Instruments and ingenuity' by Jim Bennett in Robert Hooke Tercentennial Studies, edited by Cooper & Hunter, Ashgate 2006, pp. 65-76.

[xii]. 'Hooke's design for a driven equatorial mounting' by Allan Mills, John Hennessy and Stephen Watson in Robert Hooke Tercentennial Studies, edited by Cooper & Hunter, Ashgate 2006, pp. 77-88.

[xiii]. 'Robert Hooke's seminal contribution to orbital dynamics' by Michael Nauenberg in Robert Hooke Tercentennial Studies, edited by Cooper & Hunter, Ashgate 2006, pp. 3-32. Nauenberg speculates that had Hooke in 1679 written to Leibniz instead of to Newton, the history of celestial mechanics might have been very different. One is also tempted to speculate that Newton would never have bothered to publish Principia if Hooke had not annoyed him so much.

[xiv]. 'The civic virtue of Robert Hooke' by Michael A. R. Cooper inRobert Hooke and the English Renaissance, edited by Kent & Chapman, Gracewing 2005, pp. 161-186 is a brief account.

[xv]. 'Messungen im 17. Jahrhundert - Eine Analyse aus der Sicht des 21. Jahrhunderts' by Michael Cooper & Marek Ziebart in Monumenta Guerickiana 116, Heft 14/15, Magdeburg 2006/7.

[xvi]. 'Test of the inverse-square law of gravitation using the 300m tower at Erie, Colorado' by Speake et al in Journal of Geophysical Research 96(B12): pp 20,073-20,092 (1991).

[xvii]. Robert Hooke, City Surveyor, PhD dissertation by M. A. R. Cooper, City University London, 1999 (unpublished).

[xviii]. The best contemporary description of how Hooke's team of surveyors measured London is A Sure Guide to the Practical Surveyor(1678) written by John Holwell, one of the surveyors. The 4th edition of William Leybourn's The Compleat Surveyor is more verbose and contains an overly obsequious (even for those times) dedication to Sir Thomas Player, Chamberlain of London.

[xix]. Edward Worsop's A Discoverie of Sundrie Errours and Faults Daily Committed by Landemeaters ... published in 1582 contains some amusing anecdotes about estate surveying and surveyors as well as some necessary geometry.

[xx]. A recent statistical analysis of the differences between the positions of salient features of buildings on the Ordnance Survey digital map and the positions of the same features on the 'Ogilby and Morgan' plan shows that on average the differences are of the order of only five metres across the whole area of the plan (locally the differences are much smaller). Up to two metres of the five-metre average can be attributed to distortions of the paper documents on which the 17thcentury coordinates were measured. See Is the 'A to Z' of Restoration London Accurate? by Caroline Mayo, unpublished MSc dissertation, Department of Geomatic Engineering, University College London (2001).

[xxi]. 'Hooke and Bedlam' by Jacques Heyman in Robert Hooke Tercentennial Studies, edited by Cooper & Hunter, Ashgate 2006, pp. 153-164.

[xxii]. 'Robert Hooke's Montague House: London architecture with continental flair' by Alison Stoesser in Robert Hooke Tercentennial Studies, edited by Cooper & Hunter, Ashgate 2006, pp. 165-179.

[xxiii]. 'The "Mechanick Artist" in late seventeenth-century English and French architecture ...' by Hentie Louw in Robert Hooke Tercentennial Studies, edited by Cooper & Hunter, Ashgate 2006, pp. 181-199.

[xxiv]. Repeating some of Hooke's experiments (and those of others) and knowing what questions he was trying to answer could be part of teaching science in schools (but the amount of mercury needed for Boyle's Law would rule out that particular experiment because it would be too expensive and contrary to health and safety regulations.

[xxv]. 'Hooke and Westminster' by Edward Smith in Robert Hooke Tercentennial Studies, edited by Cooper & Hunter, Ashgate 2006, pp. 219-232.

[xxvi]. 'After the Principia' by Robert D. Purrington in Robert Hooke Tercentennial Studies, edited by Cooper & Hunter, Ashgate 2006, pp. 233-246.

[xxvii]. A More Beautiful City ... by Michael Cooper, Sutton Publishing 2003 (reprinted as Robert Hooke and the Rebuilding of London, Sutton Publishing 2006) pp. 71-72.