A series of investigations using Santorio's17th century pulsilogium...

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...to help primary-age children develop scientific skills and understand the process of scientific research.

Abstract

Primary school children introduced to a long-forgotten and only recently rediscovered invention, Santorio's pulsilogium, have been able to develop their own scientific inquiry skills and deepen their understanding of the repetitive and problematic nature of scientific research and development.

We present the thoughts and ideas of children as they consider why and how a famous scientist from late 16th and early 17th century Italy developed an instrument to measure pulse. At the time of Santorio, even the best clocks did not have sufficient stability to enable pulse to be measured or expressed in beats per minute. The children were able to explain and debate in a highly effective way when they had explored the methodology of the pulsilogium, and had less difficulty than many adults in understanding the concept that the measurements obtained were comparative rather than absolute values.

Keywords: Pulse, pendulum, Santorio, measure, scientific inquiry

Introduction

In November 2015, a collaborative project involving university researchers, teachers, schoolchildren and members of the public began at the University of Exeter, UK. The aim of this project was to recreate the 17th century medical laboratory of Santorio. Santorio was a physician and professor of medicine at Padua University in the late 16th and early 17th century.

Amongst his many inventions were a number of instruments for measuring pulse, which he named *pulsilogia* (Bigotti *et al*, 2017).

In the 21st century, most of us are surrounded by instruments taking measurements: computers, tablets and mobile phones, all measuring numerous variables such as time, temperature, pulse, sugar levels, number of steps walked, to name but a few. Because it is possible to collect so much data in the modern age, we are presented with ever more statistics designed to influence and change how we live our lives. Children are growing up in media-rich homes and digital technologies are an important part of their lives (Chaudron, 2015). Recent evidence suggests that primary age children trust machines to such an extent that they will modify their behaviour to conform with robots (Vollmer *et al*, 2018). However, a digital read-out from any device is only the result of a measurement process. Sources of error are present at each stage in that process and all add to the measurement uncertainty, so a measurement has little meaning unless these sources of error are quantified and assessed. It is important that educators teach children to question data. Through a series of investigations using models of Santorio's pulsilogium, children have worked scientifically to consider how and why measurements are taken and evaluated old methods with modern technology.

Aims

We wanted to provide a project for primary school children to enable them to experience the challenges faced by real scientists, both past and present. After using a reconstruction of Santorio's pulsilogium to measure pulse with primary-age children, we thought that learning about the development of this instrument provided a suitable real-life context that children could understand.

Our aims in this project were:

- To develop children's scientific inquiry skills (planning, observing, measuring, evaluating) and scientific literacy;

- To help children consider the meaning of measurements, scales and appropriate units of measurement;
- To provide an opportunity for children to experience the nature of scientific research by solving problems, collecting data and repeating measurements, and to understand the difficulties faced by scientists in the past and today; and
- To reflect on the value of old technology and compare with new technologies by encouraging children to think about validity of the measurements and numbers produced by digital equipment.

Development of Santorio's pulsilogium

Born in 1561, Santorio studied mathematics in Venice before graduating from Padua University, where he was a contemporary of Galileo. Although for the most part forgotten, to those who study the history of medicine in the early modern period, Santorio is best known today for his discovery and study of what he called 'insensible perspiration' – what we now call metabolism. However, this was only one of his many innovative contributions to medical science. Santorio was the first person in the history of medicine to recognise the importance of precise measurement in the diagnosis of disease; to aid his work he invented 20 instruments, many of which are still in use today but in much more modern forms.

In Santorio's time, the laws of motion were only just beginning to be understood; although it was known that a pendulum could reproduce precisely timed swings provided its arc of movement was small, no one at the time understood why. Santorio was the first person to make practical use of this property when he applied it to measurement of the pulse. Like many others of his time, he knew that the period of a pendulum – the time it takes to move from its at-rest position out to one extent of its swing, back through the starting position, out to the opposite extent of its swing and then back to the centre – depends upon the length of suspension cord and is independent of the suspended mass (Nelkon & Parker, 1975). Hence, he reasoned that, by adjusting the length of the suspension cord, the motion of a pendulum could be made to synchronise with strokes of the pulse.

Santorio's beam-type pulsilogium enabled the operator to adjust the period of the pendulum whist it was in motion and read off an indirect indication of the suspension cord length from a scale marked on the beam (Bigotti *et al*, 2017).

The concept of pulse as a rate, i.e. beats per minute, was unknown to medicine at the time of Santorio, because it was not possible to measure short time intervals accurately and reliably. Most clocks at that time were not equipped with minute hands because their rate was erratic in the short term; even the best of them couldn't measure 24 hours consistently to better than ± 15 minutes (Jespersen & Fitz-Randolph, 1999).

Assessment of the quickness or slowness of the pulse at the time of Santorio was at best only an estimate, depending on the skill and experience of individual physicians. Santorio improved on this by using his pulsilogium, which is the first instrument of precision in medicine (Bigotti *et al*, 2017; Bigotti & Taylor, 2017), and expressing pulse as degrees on a numerical scale; Santorio's 'Degree of the pulse' was expressed as a single number read from a scale on the instrument. Santorio's pulsilogium is sensitive to very small changes in the pulse, which are beyond the ability of any physician to perceive unaided.

A woodcut engraving of Santorio's beam-type pulsilogium (Figure 1) shows the proportions of this instrument:

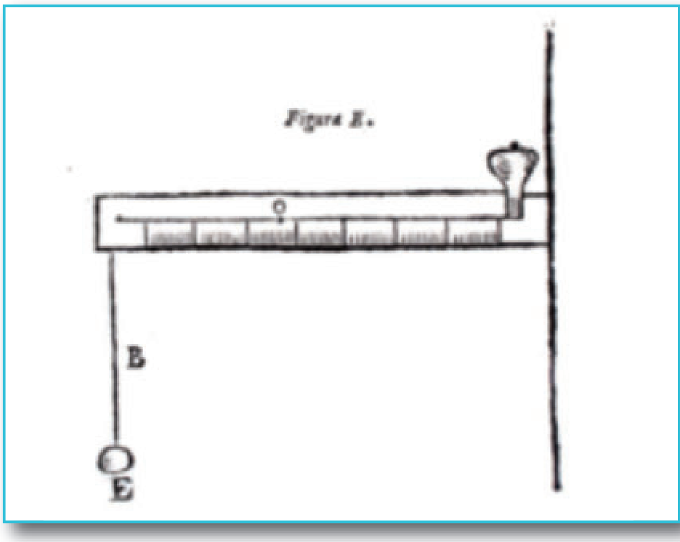


Figure 1: Original woodcut engraving of Santorio's beam-type pulsilogium. (This image is from Santorio's *Commentary to Avicenna's Canon*, published in Venice in 1625.)

Examination of the image in Figure 1 and historical records led to the sketch of the instrument shown in Figure 2, and the creation of a historically accurate reproduction (Bigotti & Taylor, 2017):

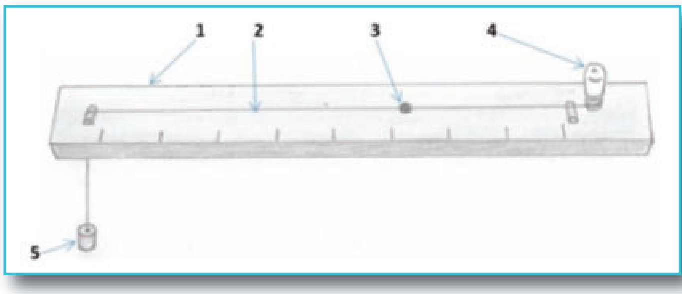


Figure 2: A sketch of a replica of Santorio's pulsilogium, where 1 is the support beam and scale; 2 is the linen thread; 3 is a bead; 4 is a tapered peg; and 5 is a pendulum bob.

Santorio's methodology for measuring pulse

Rotation of a tapered peg adjusts the length of pendulum suspension cord, which is indicated by the position of the wooden bead along the scale (Figure 2). Use of a taper enables the peg to be locked in place once set. Whilst feeling the patient's pulse, the tapered peg is rotated until the limits of the pendulum swing coincide with beats of the pulse so that there are two pulse beats per pendulum cycle. At this point, the number on the scale adjacent to the wooden bead gives an indirect indication of the speed of the pulse; this reading is recorded for future reference. Note that, as the pulsilogium is sensitive to very small changes in the pulse, it is essential that all readings are made relative to the same edge of the bead. It is easier and more reliable to read from an edge rather than estimate the position of the bead centre.

In order to compare the patient's pulse with an earlier reading, Santorio would have first set the wooden bead to the position previously noted and then compared the current pulse with the motion of the pendulum. By starting with the bead in the original position, it would be immediately obvious if the pulse had changed. After adjusting the instrument to match the current pulse, the difference between the earlier reading and the current one shows the direction and amount of change in the speed of the pulse over the intervening period; this would have been essential to Santorio when assessing his patient's condition.

A photograph of the first historically accurate reproduction of Santorio's Pulsilogium is shown in Figure 3:

Figure 3: An historically-accurate reconstruction of Santorio's beam-type pulsilogium (Bigotti *et al*, 2017).

Children's investigations

We have presented a series of investigations that enable children to think about a problem as Santorio would have done when he was developing his pulsilogium. Very few resources are required. The children work in small groups using a wooden batten, some thread, some modelling clay and a strip of paper to construct their own model pulsilogium, which they can use to measure pulse. The investigations have been carried out with children aged 7-11 years in science clubs and in STEM workshops on science days, and with adults and children at a science festival.

Initial discussion

Rather than showing and explaining how the pulsilogium works, we introduced a reproduction of Santorio's pulsilogium to the children without any explanation and asked them to consider what it might be, how it worked and to explain why they thought this (see Ritchie *et al*, 2019 for a similar approach to instruments of this kind). Teachers could show the initial few seconds of the video clip at https://youtu.be/ddfUnd5E6EU, or a picture of it (Figure 3). Alternatively, children could be shown a simple model pulsilogium (see Appendix 1 for details on how to make one).

Some initial questions that we asked children were as follows:

- *What do you think this might be?*
- *Have you seen one before? Where? When?*
- *Which parts move?*
- *What does the scale tell you?*
- *What are the units of measurement?*
- *How would you use it?*
- *What would it measure?*

At this stage, the children do not know that the string can be lengthened and shortened. We found that responses from the children varied depending on their age and their prior experiences (as found by Ritchie *et al*, 2019) but, with support, most children made good suggestions and linked their ideas to evidence from their own experiences.

Here are some typical responses from children:

- *'I think it is a spirit level because it is long and horizontal'* (age 10).
- *'I think it is a weight measurer because you can put different weights on the end of the string'* (age 9).
- *'I think it is a stethoscope because you can put this part [indicates the bob on the end of the cord] on to your heart and it will measure through the string'* (age 9).

Here is an opportunity for children (with support from the teacher) to articulate scientific concepts, explore their ideas and address any misconceptions held in science. Though one child did suggest that the instrument could measure pulse through the string, they did not predict that the string was a part of a pendulum. None of the children we worked with proposed that the instrument measured pulse by synchronising the motion of a pendulum, and they were fascinated when we explained that this instrument was first made in about 1602 by an Italian scientist called Santorio, who used it for measuring the pulse of his patients.

Finding a pulse

Many children will have had their pulse measured in hospital or by their GP, so this is a good starting point for talking about pulse. Ask if any of the children can explain what was measured and how it was done. We found that many children aged over 7 years knew that their pulse is the heartbeat felt at different parts of their body, because they were old enough to have experienced visits to the doctor or hospital. We found that some children who have experienced a stay in hospital remember having a pulse meter put on their finger. Others remembered a tourniquet being put on their arm and others have had a stethoscope placed on their chest or back. You may find that you have a lively debate about where and how a pulse can be felt. Whilst it is good to mention several areas where the pulse can be felt, encourage the children to feel the pulse in their wrists, as this is the focus of the experiments here.

Units of measure – speculation and reasoning

We asked the children whether they knew in what units their pulse was measured. We found that some children describe pulse as 'number of beats' but do not know that it is measured as 'beats per minute'. A few of the older children were able to explain that beats are counted for a fixed time period so that the result is expressed as beats per minute. Note that it is not necessary at this stage to demonstrate measuring a child's pulse in beats per minute, as this may confuse the pulsilogium investigation. The children just need to be able to feel their pulse or a partner's pulse using two fingers (index and middle) on the wrist.

Having established that pulse beats could be counted for a fixed time period, we explained that, in 1600, there were no reliable clocks for Santorio to use. Ask the children if they can guess what Santorio did with his pulsilogium? Interestingly, we found that many children suggested putting the weight of the pendulum on the wrist, imagining that electricity (or perhaps infrared light) travelled along the cord to the numbers on the scale to provide a numerical reading. It is a reasonable suggestion when, in a child's life, so many things are made to happen as a result of electricity travelling through wires. Perhaps no more incredible than pointing a gadget at a machine to operate it when it isn't even attached; very few children have not used a remote control to operate a TV before they come to school. Encourage the children's ideas and talk about why some of the children's thoughts may or may not work, either now or in Santorio's day (Osborne, 2010; Mercer *et al*, 2009). It is worth saying at this stage that children should be given time to justify their ideas, even if they are not plausible and, similarly, children need time to consider and evaluate alternative ideas suggested by their peers (Mercer *et al*, 2009). A skilled practitioner will provide opportunities to consider not only why a 'right' idea is 'right', but also why a 'wrong' idea is 'wrong'. Using sentence starters can help children to develop skills of argumentation, e.g. *'I think … because …'*, or *'I don't agree because …'* (Mercer *et al*, 2009) and exemplified, for example, by Eley (2016). Just like scientists throughout history, children need to know that it is okay to say *'I've changed my mind. Now I think …'*. By following this approach, children will have a better understanding of the nature of scientific inquiry and the way in which scientists work when discussing their research.

Measuring pulse with a model pulsilogium

Show the children how to start the pendulum by holding the weight about 30 degrees (not more than 45 degrees) from the vertical and letting go (no need to push), and how to count the swing of the pendulum. This is easiest to do by counting at the limits of the pendulum swing, i.e. two pulse beats per pendulum cycle. Ask a child to count aloud in time with the pendulum. The next bit is trickier and needs to be done by a child who is confident in finding a pulse in someone's arm. This child should count aloud the beats of the pulse that they feel. Ask the group whether these two beats are 'synchronised' (occurring together). Explain that Santorio was able to obtain a value for the patient's pulse when it was synchronised with the pendulum. Ask for the children's suggestions as to how to adjust the swing of the pendulum so that the limits of its swing coincide with the pulse beats. Discuss their ideas, encouraging children to explain why they agree or disagree with others, as this allows the children to develop scientific literacy and demonstrates how to question the ideas of others in a positive and constructive way. The thread length should be shortened to quicken the swing of the pendulum and lengthened to slow it down.

Choosing a scale for the pulsilogium

Once the children can synchronise the swing of the pendulum on their pulsilogium with the 'patient's' pulse, the investigation moves on to ask the children what scale is needed on the pulsilogium:

- *How can you show that the pulses of people are different?*
- *How will you show that the thread is longer or shorter?*
- *Can you suggest a suitable scale to put on the beam?*
- *Will your scale use numbers or words or symbols to describe a person's pulse?*

It is interesting to hear the children's suggestions for scales. If they have seen one of the experimental reconstructions of Santorio's instrument, they may suggest centimetres because they saw that a metric tape measure was used to represent the scale. When we asked children for suggestions for scales along the beam, we found that they either chose some units associated with measuring length that they previously had heard of (cm or inches), or they wanted to invent a new scale with numbers.

Suggestions from children aged 9-11 years included:

- *'We could use a Lego brick to mark equal distances on the paper strip.'*
- *'Use your thumb to mark lines along the paper.'*
- *'Use a ruler [presumably a metric one] and put a mark every 5 cm.'*

When we have asked children in what units their pulse is measured, some were not able to provide an answer, but most explained that *'It cannot be cm'*. Responses from children included:

- *'It can't be centimetres because it's not "how long" is your blood.'*
- *'It isn't beats per minute because we didn't count for a whole minute.'*
- *'If we use Lego bricks, we can measure it in bricks.'*
- *'Measure it in thumbs using thumb prints.'*

Children appear not to have fixed ideas of units of measurement for the pulsilogium. Some children have asked, without prompting: *'Why do you need numbers when you could have pictures?'* Why indeed, when an emoji can explain just how 'well' a patient is or isn't (Figure 4)! A child who had musical instrument lessons decided to add musical terms to describe the speed of the pendulum and rate of the pulse: *adagio* and *largo.*

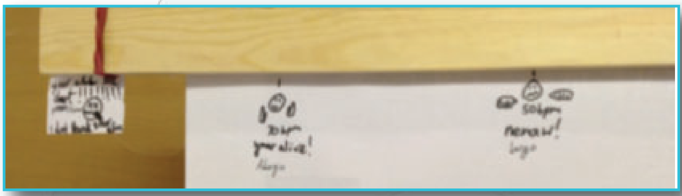


Figure 4: Children's emoji scales and musical terms on a model pulsilogium.

We discovered that adults, on the other hand, have preconceived ideas about measuring pulse and find it hard to remove 'beats per minute' from their minds. Some believe that the number marked on a cm scale on the beam is a value equivalent to beats per minute. At a public demonstration of Santorio's pulsilogium at a science festival, eight adults allowed us to synchronise the pendulum with their pulse. The scale on the pulsilogium beam was a metric tape measure. Indirect measures of pulse were taken from the scale and ranged from 29 to 48. More than one adult asked *'Is my pulse 30 beats per minute?'* Clearly, this cannot be the case: most adults have a resting heart rate between 60 and 100 beats per minute (NHS website, 2019). We also measured their pulse with a pulse meter and the range was 68 to 80 beats per minute.

Testing reliability

Once the children are confident using their pulsilogium and have recorded the pulse of a few people (using a numerical scale, a word scale or emojis), the next step is to determine how **reliable** the pulsilogium is to measure pulse**.** We know from controlled experiments that the pulsilogium is very accurate and reliable when tested by a trained operator against a stable source, i.e. a metronome (Bigotti & Taylor, 2017)**.** However, in practice, pulse measurements could be affected by:

- ***Biological error*** (internal error), meaning the natural variation in a person's resting pulse, as pulse rate is sensitive to many factors including emotions, illness, environmental conditions and previous exercise.
- ***Experimental error*** incurred by the persons taking the measurements (in the case of the pulsilogium, this could be two or three people), and two sources of variation need to be considered**:** firstly, **within observer variation** (how similar are the results of repeated measurements taken by the same person/group using a single pulsilogium?); secondly, **between observer variation** (how similar are pulse readings taken by different people on the same patient using the same pulsilogium?).
- ***Instrument error,*** meaning the variations in the behaviour of the equipment.
- ***Environmental influences,*** such as variations in temperature and humidity.

Ask the children:

- *What might affect the reading you observe from your pulsilogium?*
- *How will you know if your pulsilogium is reliable?*
- *How many times will you repeat your measurements?*
- *What could you do to try to reduce variability in your measurements?*

To address biological error, simple measures to reduce variation within the 'patient' could include asking them to lie very still with their eyes closed for five minutes before the measurements are taken.

Children should consider their sources of experimental error: whether the person counting the pulse ('pulse monitor') is accurate, whether the person counting the pendulum swings ('pendulum monitor') is accurate, whether the two 'monitors' are properly synchronised.

In the case of instrument error, consider what this could be for the pulsilogium:

- The pulsilogium might not be horizontal – this doesn't matter as long as the pendulum swing is not impeded.
- The swing of the pendulum might have been greater than 30 degrees from vertical.
- The pendulum swing started by a child might have been unsteady.
- A pendulum does not always swing in a straight line; sometimes the motion of the pendulum bob describes an ellipse or a figure of 8.

Encourage the children to repeat their pulse measurements, whilst keeping as many variables as possible the same. This may be challenging because the children may want to swap roles but, to properly investigate reliability, the patient, the pulse monitor and the swing monitor should be unchanged. It is worth reminding children that the nature of science research is repetitive and, as a result, is not always exciting during the data collection. It is, nevertheless, vital to the process of research and can lead to exciting findings.

We found that pulse readings in most cases were reliable using a pulsilogium with a hand-drawn number scale as shown in Figure 5. In this case, the same two children took the role of pulse monitor and pendulum monitor to reduce experimental error. They recorded indirect measurements of pulse for three different 'patients' and repeated their tests after about 30 minutes. In two patients, the second reading of pulse was very similar to the first. The change observed in the third child's readings was a source of speculation and the children suggested that the pulse increased because the 'patient' had been moving around so much (biological error) rather than a result of any observer variations (experimental error).

It is worth noting that the pulsilogia built in any one classroom will have different scales and so it will not be possible to compare these instruments directly with each other. Instead, they can all be compared with another instrument counting pulse, such as a metronome or an electronic metronome (Figure 6). The children used a metronome app on a mobile phone to produce 70 beats per minute and compared this with their pulsilogium reading. Every time they repeated this, the children were delighted that the indirect reading on their pulsilogium was very close (usually the marker on the thread moved less than 2 cm) to their original reading.

We noticed at this stage that the children were thinking about how to make their instruments more accurate and asking questions about improving the reliability of their instrument and their methodology:

- *'The marker is too wide, and we don't know which edge to look at – can we make the marker on the thread narrower?'*
- *'How can we make sure the patient is properly rested – shall we time them sitting still?'*

Comparisons with other methods of measuring pulse

Having repeated pulse measurements on the pulsilogium, the children should now have some understanding of whether their pulsilogium is reliable, but what about other more modern instruments that we use to measure pulse?

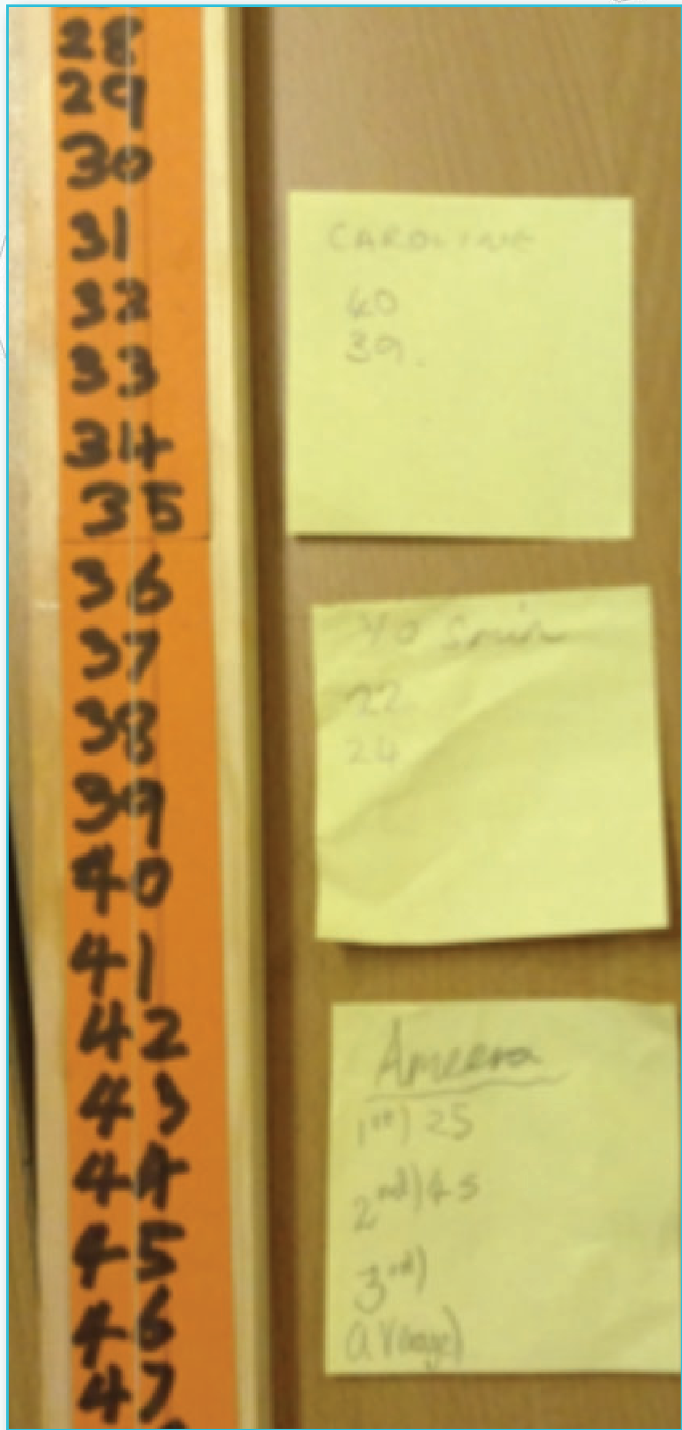


Figure 5: Repeated pulse measurements using a basic pulsilogium.

Figure 6: Children compare pulsilogium data with a metronome app.

Show the children how to measure their pulse by counting for a fixed period, for example, count pulse beats in the wrist for 15 seconds and multiply by 4 to ascertain the beats per minute. There is only one source of human error with this method. Children can compare reliability by taking repeat measurements by having two children recording the pulse of a third (one on each arm). What do the children think about the reliability of this method? How does it compare with the measurements they took on the pulsilogium?

Next the children could investigate the reliability of a modern pulse meter. These can be borrowed from a local GP surgery. Again, encourage the children to take repeat readings to determine the instrument's reliability and have children compare two pulse meters if possible, to find out how reliable the modern pulse meter is. If only one pulse meter is available, the children can simply compare their pulse that they counted in the first method with their pulse read from the pulse meter. They could be surprised by the results. Several wrist-worn heart rate monitors are available now. If you can borrow one of these, the children will be able to compare the reliability of these instruments too.

After looking at some different methods of measuring pulse, there are some important questions to consider with the children:

- *Which method do you think is the best for measuring someone's pulse?*
- *Can you say why this method is best?*
- *Are you surprised by any of your results?*
- *Are electronic / computerised instruments always the most reliable?*
- *What are the main sources of error in measuring pulse in each method?*

The last question is a big one to consider, but it is an important one for children because they are growing up in a digital world and are using technology in so many aspects of their lives. How reliable is technology? Modern instruments are also susceptible to error; differences have been shown between measurements taken by various makes and models of wrist-worn monitors (Kooiman *et al*, 2015; Shcherbina *et al*, 2017). It is very important to emphasise that 'digital' does not necessarily mean 'accurate'.

Other pendulum investigations

What happens to the pendulum period when the arc through which it swings is changed?

Ask the children to predict whether the pendulum period will be greater, less or unchanged if we change the angle from vertical that the pendulum is released from. The children could draw angles between 10 and 40 degrees from vertical on card and attach to the table behind the pendulum (Figure 7).

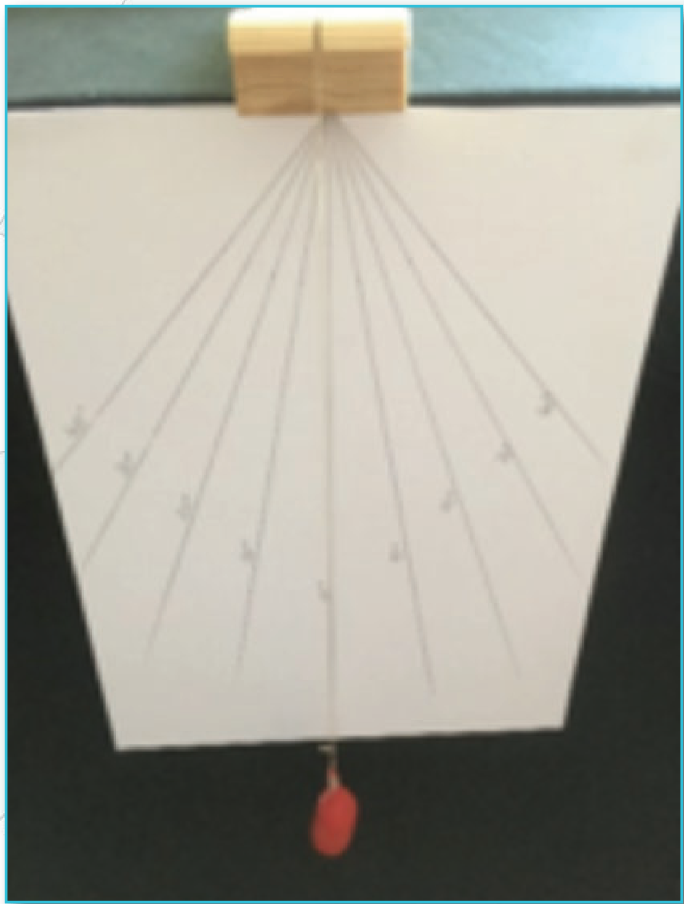
This would allow the children to release the pendulum from different angles and to record any variations: children could either count the number of complete oscillations in a fixed time period (we used 30 seconds) or use a timer to record the time taken for a fixed number of periods.

It would be interesting for children to compare these methods and this allows children to appreciate that questions can be investigated and answered in different ways. The children should find that the period does not depend on the amplitude, provided the angle is kept small (less than 30 degrees).

What happens to the pendulum swing when the pendulum mass is changed?

Provide weighing scales and ask the children to investigate what happens to the pendulum period when the mass of the pendulum 'bob' is increased.

Figure 7: Investigating the arc angle of the pendulum.



Again, children can either count oscillations in a fixed time period or record the time for an agreed number of oscillations. The children should find the mass of their modelling clay bob has no effect on the pendulum period.

Where else is a pendulum used?
Ask the children where they have seen a pendulum used. Some may have seen grandfather clocks. Children can research how the pendulum is used to move parts within the clock mechanism to record time.

How can the pendulum be used to divide time? (Egg timer investigation)
Provide the children with a 1-minute sand timer and ask them to create a pendulum that can record 1 minute. If the children have previously investigated the effect of the pendulum weight and angle of swing, they will know that only the length of pendulum needs to be changed to influence the period. Can they change the length of the thread so that the pendulum swings a fixed number of times in one minute? Can the children then tell you the time taken for one period? Can they predict how many periods they will need to count for 3 minutes? Children can test this out using a 3-minute timer to see if their predictions are correct.

Discussion

Our main aim in creating these investigations was to develop children's scientific inquiry skills (Mercer *et al*, 2009). Introducing Santorio's 17th century pulsilogium to primary-age children and exploring its history, development and reliability provides an opportunity for inquiry-based teaching and the development of children's science inquiry skills. This teaching approach, when learners try to make sense of new experiences or solve a problem, is well documented (Harlen, 2014; Harlen, 2018). Children undertaking inquiry in science will: plan how to investigate, work collaboratively with others, gather data, interpret data, express their ideas using appropriate scientific terms, and reflect about the processes and outcomes of their inquiries. In these pulsilogium investigations, children had to work collaboratively because to operate a pulsilogium requires the co-operation of others. We observed the children planning how they would adjust the length of the pendulum whilst it was in motion, organising different roles for members of the group, choosing a satisfactory scale for the instrument, deciding who would determine that the pulse and pendulum were synchronised. Throughout this activity, the children were using science vocabulary to explain to each other when the pendulum needed to be made longer or shorter, to suggest and consider improvements to their methodology and to compare their pulse readings. We also noticed that, as the children started using the pulsilogium, they started asking more questions (as described in 'Testing reliability'), an important skill to foster for practising scientists (Vale, 2013). We suggest that all these experiences will help children to develop scientific literacy: to appreciate and understand the impact of science and technology on everyday life; to take informed personal decisions about things that involve science; and to take part confidently in discussions with others about issues involving science (Nuffield Foundation, 2019).

There are strong arguments in favour of inquiry-based teaching: increased student engagement and deeper understanding of science concepts (Mercer *et al*, 2009) and improvements in student achievement (Blanchard *et al*, 2010; Minner *et al*, 2010; Hmelo-Silver *et al*, 2006). In contrast, the PISA survey of science literacy in 15 year-olds suggested that teacher-directed instruction may be associated with higher student achievement (OECD, 2018), and other reports have suggested that 'minimally guided instruction' is less effective and less efficient than more direct instructional approaches (Kirschner *et al*, 2006). It should be noted that the work of Kirschner *et al* (2006) has been challenged by a number of researchers (e.g. Hmelo-Silver *et al*, 2007), but the consensus is that some scaffolding is required to produce effective results. In addition, it has been suggested that practical inquiries in the classroom do not always include time for reflection and discussion (Osborne & Miller, 2017). At every stage of these pulsilogium investigations, children were encouraged to reflect on their learning; to justify their ideas on the purpose of the pulsilogium in the initial discussion; to consider the merits of different units of measure in the development of a model pulsilogium; and to evaluate the reliability of the 17th century instrument and modern instruments when measuring pulse. We believe that working through these investigations will have a positive impact on children's practical science skills and scientific literacy because, at several stages, the children are encouraged to justify their ideas, consider the ideas of others and revise their initial thoughts (Appleton, 2002).

The series of investigations we have described provide opportunities to explore several types of inquiry (e.g. Appleton, 2002; Turner *et al*, 2011). By asking children 'Which is best?' when considering scales and units, the children experience comparative testing. By asking 'What happens when… you repeat your pulse reading?' or 'What happens when…the patient has rested/exercised before the reading?', the children are required to make observations. Towards the end of the series of pulsilogium investigations, we suggest other activities that children could carry out with a pendulum: changing the mass of the pendulum bob or the arc of the pendulum oscillation. Both investigations are pattern-seeking. We also suggest asking 'Where else is a pendulum used?' and finding out more about digital methods to measure pulse – these require research from secondary sources. The project also includes many opportunities for problem-solving by asking 'How can we…?' questions such as: 'How can we change the pendulum speed whilst in motion?', 'How can we know when the pendulum and pulse are synchronised?' and 'How can we be sure the instrument is reliable?'.

Our second aim was to help children to understand measurement: What is measurement for? What does the measured value tell us? Is the measurement reliable? Giving the children the freedom to choose a scale for their own pulsilogium encouraged them to think about what the numbers or words on the scale mean. They understood the principle of an 'indirect' measurement of pulse taken from a number on the pulsilogium beam, which has nothing to do with a pulse rate, though this was challenging for some adults. The children developed skills of measuring and gathering data and acquired a deeper understanding of measure, because they considered the types of scales and units appropriate for the measurement before they collected their data and had no hesitation in introducing novel scales (see the children's comments that we documented in 'Choosing a scale for the pulsilogium'). The children observed that different scales on different instruments produced different measurements, but became aware that what was important was whether the measurement could be repeated.

We hoped that following the work of a real scientist (though from a very different era) would show children how one scientist approached a problem and tried to solve it. The skills that Santorio exhibited are not very different from those a scientist needs today, or the ones that the children experienced in the classroom: they start with some knowledge, they become aware of a problem, they ask a question, they do something (usually practical) to gather data that provide evidence to resolve the problem and, consequently, they acquire some new knowledge.

The practical stage can be very time-consuming and repetitive and sometimes the new knowledge reveals a new question, leading to more practical work. We believe that the children working on this project deepened their understanding of the repetitive and problematic nature of scientific research and development. They realised that the research process can be slow, that they needed to repeat their results to be sure of reliability and that this could be quite a dull process, but a necessary one. They also became aware that teamwork is important to make progress.

Lastly, we hoped that children would reflect on the value of old technology. The children were excited that their pulse readings were similar when they repeated the measuring process with the pulsilogium (Figure 5) and that a digital metronome synchronised to the pulsilogium also repeatedly produced the same readings on the scale (Figure 6). They were surprised when the pulse meters took time to settle and sometimes produced different pulse rate readings for the same resting patient. Although the children did not repeat any individual's pulse reading more than twice, it was enough to see that measuring and collecting data using an old technology was reproducible.

The history of the pulsilogium and its methodology could be developed further. It offers teachers opportunities to develop a range of cross-curricular topics: for example, to develop a general topic on 'time' (comparing modern clocks with the pulsilogium as a device to measure time), or health, or designing machines. Within any of these topics, teaching and learning could include history, geography, Design Technology (DT) and maths. Questions that pupils could investigate in science are: What did scientists know at the time of Santorio? What did other scientists try to find out? What were the limitations of science research in the 17th century? In geography, the focus could be on Italy or looking at other cultures and countries that have produced famous scientists. In DT, pupils could design, make and compare different pulsilogia and, in maths, they could investigate different units of scales.

Conclusions

Learning about Santorio's 17th century pulsilogium is not part of any science curriculum, but we believe that, through this series of investigations, children can develop their scientific inquiry skills, improve their scientific literacy and acquire an appreciation of the nature of scientific research. It does support the idea of looking at famous scientists and makes important cross-curricular links.

By following the development of a real scientific instrument, even one from 400 years ago, children experience the repetitive and slow nature of scientific research in a context that is meaningful to them. They develop their inquiry skills by taking on the role of a real scientist: to observe, to ask questions, to suggest answers and ways to test their ideas, to explain their findings and to evaluate their own investigations. Children begin to appreciate that science research is about collecting measurements and checking that they can be repeated. Having this historical context provides engaging opportunities for children to debate and solve problems that were real for a scientist.

Using and developing the pulsilogium enables children to investigate different scales used for comparing measurements. Choosing symbols rather than numerical scales helps children to appreciate that measurements can have non-standard units. Having made up new empirical scales of their own, children become aware that scales are man-made constructs and that they only have meaning if the measurements taken from them are accurate and can be reliably repeated. Looking at alternative units for a scale reminds children that the units of measure that they are familiar with (e.g. metres, kilogrammes and seconds) were established not so long ago and have been a crucial development in science research; establishing international standards for weights and measures allows scientists across the world to make meaningful comparisons between data.

Children may be surprised to discover that an old technology (without electricity or microchips) is possibly a more reliable method of measurement than equivalent modern technologies.

The investigations described have demonstrated that children of primary school age understand the difficulties faced by historical scientists and that they can reason and solve problems in a logical way.

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References

Appleton, K. (2002) 'Science activities that work: Perceptions of primary school teachers', *Research in Science Education*, (32), 393–410

Bigotti, F. & Taylor, D. (2017) 'The Pulsilogium of Santorio – New Light on Technology and Measurement in Early Modern Medicine. Pendulum Clocks in the Seventeenth Century', *Philosophy, Society and Politics*, **11**, (2), 55–114. Retrieved from: http://socpol.uvvg.ro/index.php?option=com_content&view=article&id=221&Itemid=238

Bigotti, F., Taylor, D. & Welsman, J. (2017) 'Recreating the Pulsilogium of Santorio: Outlines for a Historically-Engaged Endeavour', *Bulletin of the Scientific Instrument Society*, (133), 30–35. Retrieved from: https://static1.squarespace.com/static/54ec9b40e4b02904f4e09b74/t/59ae832ed7bdcecfe13b5fb4/1504609073145/Bulletin_133_Pulsilogium.pdf

Blanchard, M.R., Southerland, S.A., Osborne, J.W., Sampson, V.D., Annetta, L.A. & Granger, E.M. (2010) 'Is inquiry possible in light of accountability?: A quantitative comparison of the relative effectiveness of guided inquiry and verification laboratory instruction', *Science Education*, (94), 577–616. Retrieved from: https://onlinelibrary.wiley.com/doi/abs/10.1002/sce.20390

Chaudron, S. (2015) 'Young children (0-8) and digital technology. A qualitative exploratory study across seven countries', *Report EUR 27052 EN, European Commission Joint Research Centre*, DOI:10.2788/00749: http://www.lse.ac.uk/media@lse/research/ToddlersAndTablets/RelevantPublications/Young-Children-(0-8)-and-Digital-Technology.pdf

Eley, A. (2016) 'How the "I Can Explain!" project helps children learn science through talk', *Primary Science*, (142), 14–16

Harlen, W. (2014) 'Inquiry-based science education: rationale and goals'. In *Assessment & Inquiry-Based Science Education: Issues in Policy and Practice*, Bell, D., Dolin, J., Léna, P., Peers, S., Person, X., Rowell, P. & Saltiel, E. (Eds.), Global Network of Science Academies (IAP) Science Education Programme (SEP), pps. 11–15

Harlen, W. (2018) 'Learning through Inquiry'. In *The Teaching of Science in Primary Schools.* Harlen, W. & Qualter, A. Routledge, pps. 106–119

Hmelo-Silver, C., Duncan, R. & Chinn, C. (2007) 'Scaffolding and achievement in problem-based and inquiry learning: a response to Kirschner, Sweller, and Clark (2006)', *Educational Psychologist*, **42**, (2), 99–107

Jespersen, J. & Fitz-Randolph, J. (1999) 'Early Clocks'. In *From Sundials to Atomic Clocks – Understanding Time and Frequency*, Jespersen, J. & Fitz-Randolph, J. National Institute of Standards and Technology, Monograph 155, 1999 Edition, pps. 36–37

Kirschner, P.A., Sweller, J. & Clark, R.E. (2006) 'Why Minimal Guidance During Instruction Does Not Work: An Analysis of the Failure of Constructivist, Discovery, Problem-Based, Experiential, and Inquiry-Based Teaching', *Educational Psychologist*, (41), 75–86. https://doi.org/10.1207/s15326985ep4102_1

Kooiman, T.J.M., Dontje, M.L., Sprenger, S.R., Krijnen, W.P., van der Schans, C.P. & de Groot, M. (2015) 'Reliability and validity of ten consumer activity trackers', *Sports Science, Medicine and Rehabilitation*, DOI 10.1186/s13102-015-0018-5

Mercer, N., Dawes, L. & Staarman, J.K. (2009) 'Dialogic teaching in the primary science classroom', *Language and Education*, (23), 353–369

Minner, D.D., Levy, A. J. & Century, J. (2010) 'Inquiry-Based Science Instruction—What Is It and Does It Matter? Results from a Research Synthesis Years 1984 to 2002', *Journal of Research in Science Teaching*, **47**, (4), 474–496

Nelkon, M. & Parker, P. (1975) *Advanced Level Physics, Third edition.* Heinemann Educational Books, pps. 48–49

NHS website (2019) 'What's a normal pulse rate?'. Retrieved from: https://www.nhs.uk/common-health-questions/accidents-first-aid-and-treatments/how-do-i-check-my-pulse/#whats-a-normal-heart-rate

Nuffield Foundation (2019) 'Twenty-first century science'. Retrieved from: http://www.nuffieldfoundation.org/twenty-first-century-science/scientific-literacy

OECD (2016) 'PISA 2015 Results in focus'. Retrieved from: https://www.oecd.org/pisa/pisa-2015-results-in-focus.pdf

Osborne J. (2010) 'Arguing to learn in science: The role of collaborative, critical discourse', *Science*, (328), 463–466

Ritchie, R.M., Franklin, S.D., Harrison, T.G., Sainsbury, P., Tyler, P., Grimshaw, M. & Shallcross, D.E. (2019) 'Exploring some simple machines and their applications', *Journal of Emergent Science*, (16), 35–39

Shcherbina, A., Mattsson, C.M., Waggott, D., Salisbury, H., Christle, J.W., Hastie, T., Wheeler, T.M. & Ashley, E.A. (2017) 'Accuracy in Wrist-Worn, Sensor-Based Measurements of Heart Rate and Energy Expenditure in a Diverse Cohort', *Journal of Personalised Medicine*, **7**, (3), 6–10

Turner, J., Keogh, B., Naylor, S. & Lawrence, L. (2011) *It's not fair – or is it?* Millgate House Education

Vale, R.D. (2013) 'The value of asking questions', *Mol Biol Cell*, **24,** (6), 680–682

Vollmer, A., Read, R., Trippas, D. & Belpaeme, T. (2018) 'Children conform, adults resist: A robot group induced peer pressure on normative social conformity', *Science Robotics*, DOI: 10.1126/scirobotics.aat7111

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See Appendix on next page.

Appendix 1

Making a simple pulsilogium

To make a pulsilogium (Figure 7a), we used a wooden batten (4.5 x 1.5 x 90 cm), a piece of D-profile moulding cut to the same width as the batten, 2 m of thread (we found that linen is best because it does not stretch), a small piece of modelling clay for the pendulum bob, a small self-adhesive label to attach to the thread as a marker, a rubber band and a strip of paper for the scale. We cut a slot a few millimetres into the centre of one edge of the D-profile and glued this (PVA glue will work), overlapping the end of the batten as shown in Figures 7b and 7c. The purpose of the D-profile is to raise the thread above the surface of the batten whilst at the same time ensuring unrestricted movement of the thread where it changes direction. A rubber band was wrapped around the other end of the beam to hold one end of the thread in place. The thread was laid along the beam and in the slit in the D-profile. About 30 g of modelling clay was attached to the free end of thread suspended under the D-profile to act as a pendulum bob.

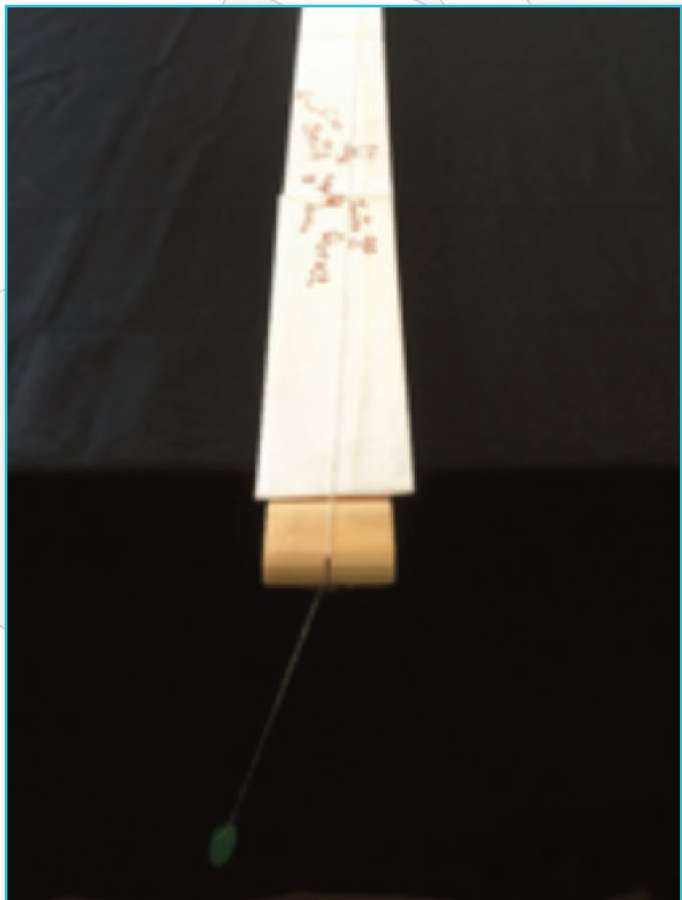

Figure 7a: A simple pulsilogium.

The instrument should be calibrated by adjusting the vertical section of thread so that the distance from the underside of the D profile to centre-mass is around 70 cm. A small self-adhesive label should then be fixed to the horizontal thread halfway along the beam. We found that this puts the marker at the centre of the measurement range for a typical resting heart rate.

Figure 7b: Side view of a simple pulsilogium showing the D-piece and pendulum bob.

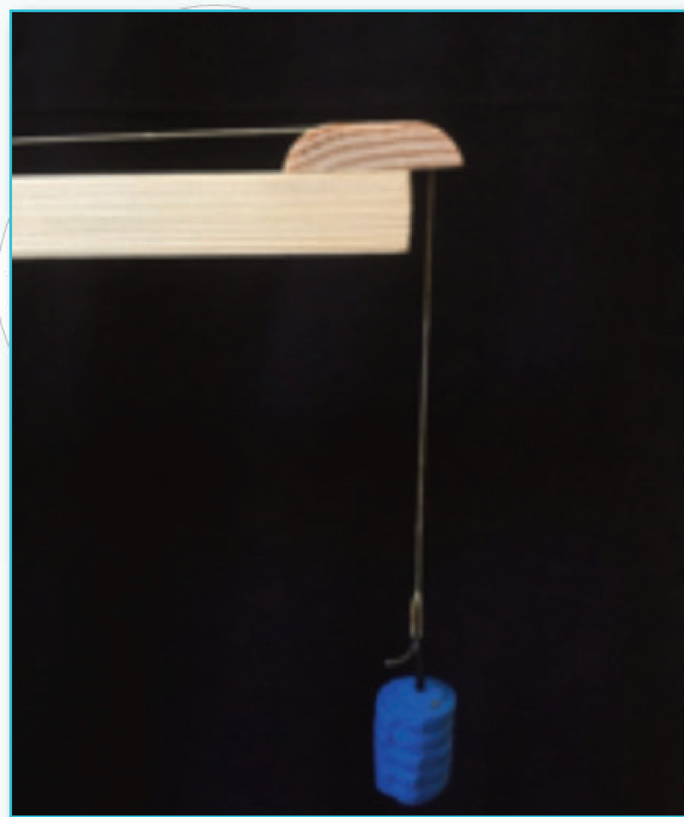

Figure 7c: A groove cut in the D-piece holds the pendulum thread.