Petrus van Musschenbroek (1692-1761) and the early Leiden jar: A discussion of the neglected manuscripts

Acknowledgments

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Introduction

In this article, I discuss manuscript material written by Petrus van Musschenbroek (1692-1761) related to his first experiments with the Leiden jar. Despite the importance of the discovery of the Leiden jar for the history of electricity and the questions that still surround it, a detailed treatment of this manuscript material is lacking in the literature.

The main aim of this paper is to provide an outline of the manuscript material and to contextualize van Musschenbroek's first experiments with the Leiden jar. I show how these experiment fits within his research program on electricity and I discuss van Musschenbroek's initial reactions to and analysis of the phenomenon.[1] Before doing so, I first provide a short overview of the treatment of the early history of the Leiden jar in the secondary literature. After that, I discuss van Musschenbroek's treatment of the topic of electricity in the textbooks that he published in the years before the discovery. We will see that van Musschenbroek repeatedly emphasized that not enough experimental results were available in order for an informed theoretical treatment of the phenomenon of electricity to be possible. Then I turn to the manuscript material. I give a general description of the contents of the manuscript and van Musschenbroek's experimental practice.

The manuscript material further confirms recent work on the Leiden jar by Cibelle Celestino Silva and Peter Heering, but also provides new insights into the way van Musschenbroek himself reacted to the discovery. Whereas Silva and Heering start with the discovery itself and look at later replications and the general reception of the experiment, the present article provides further information on the immediate context of the discovery itself and the intellectual and experimental circumstances in which it was made. The manuscript material also sheds light on the way the experiment with the Leiden jar fits within van Musschenbroek's broader research program on electricity. More specifically, it shows how van Musschenbroek's research on electricity and his reaction to the phenomenon of the Leiden jar exemplify his more general views on experimental methodology. As such, the present article is also relevant for those interested in the history of (eighteenth-century) experimental methodology.

In his own time, van Musschenbroek was a well-known and celebrated experimentalist. In the context of research on electricity his textbook was explicitly referred to as the most complete and relevant overview of the state of the art. As such, it provided the starting point for several other experimentalists.[2] Van Musschenbroek's reputation even prompted Benjamin Franklin (1705-1790) to write him a letter asking for further relevant literature on the topic of electricity.[3] Therefore, by reading the manuscript material on the Leiden jar in the light of van Musschenbroek's earlier textbook passages on electricity, this article will also interest those working on the general history of electricity in the eighteenth century.

The early history of the Leiden jar in the secondary literature

Despite the fame of the Leiden jar, van Musschenbroek's first experiments with it have not received a detailed analysis in the literature. This is probably due to the lack of source material. As John Heilbron notes, accounts are mostly based on van Musschenbroek's letter to René Antoine Ferchault de Réaumur (1638-1757) and Joseph Priestley (1733-1804)'s account in his *History of Electricity* (1767).[4] Heilbron himself provides a reassessment of van Musschenbroek's work based on a letter from van Musschenbroek to Georg Matthias Bose (1710-1761), which was published in the latter's *Tentamina electrica* (1747).[5] A recent article on the Leiden jar by Cibelle Celestino Silva and Peter Heering, although it criticises certain aspects of Heilbron's interpretation, is based on the same historical material.[6] In Cornelis (Kees) de Pater's monograph, which to date contains the most elaborate treatment of van Musschenbroek's life and works, only a small section is devoted to the Leiden jar. There, de Pater mostly follows the narrative provided by Heilbron.[7]

In the aforementioned article, Heilbron points to the crucial role of Bose's work for the discovery of the Leiden jar. According to Heilbron, van Musschenbroek "was not, in fact, a very imaginative electrician" and since his "usual procedure in studying electricity was to repeat earlier work, it is very likely that the experiments which so unexpectedly culminated in the Leyden jar also began as a repetition."[8] Further evidence for this reading is provided by the fact that in the aforementioned letter, van Musschenbroek acknowledges his debt to Bose.[9] Contrary to this negative assessment of van Musschenbroek's experimental work, we will see that van Musschenbroek's research into electricity was more systematic and less superficial than Heilbron's comments suggest.

Another central aspect of Heilbron's interpretation of the early history of the Leiden jar is his view on the role of the so-called "Rule of Dufay" in electrical research and its implications for our understanding of not only the process leading to the discovery of the Leiden jar, but also the first reactions to this discovery. The Rule of Dufay (a term coined by Heilbron himself) refers to Charles du Fay (1698-1739)'s description of the procedure that should be followed to electrify water. If one wants to electrify water, either by holding an electrified glass tube near it or by putting a metal wire connected to an electrified tube into the water, one should put the water in a glass or porcelain jar and place the jar in turn on a wax or glass support.[10] Put more generally, the rule stated that in order to electrify a body "the body to be electrified had to rest upon an electric support of sufficient thickness, or, as we would say, had to be properly insulated."[11] According to Heilbron, this was a general rule, which guided electrical research "until an apparent violation of it forced a revolution in electrical theory."[12] This violation is of course the working of the Leiden jar, which, according to Heilbron, involved the necessity of *grounding* the jar (for example by holding it in one's hands) instead of *insulating* it.

Based on his views on the importance of grounding, Heilbron also suggests that it is probable that Andreas Cunaeus (1712-88), a lawyer and friend of van Musschenbroek, was responsible for performing the first experiment with a Leiden jar. Being well-versed in electrical theory, van Musschenbroek would have duly followed the common procedure and would have insulated the jar. Only an amateur such as Cunaeus could have stumbled upon the result: "in trying to repeat the professor's manipulations, the less knowledgeable Cunaeus could easily have blundered into grounding the external surface of the vessel, thereby transforming Bose's modest fireworks into the terrible Leyden jar."[13]

Silva and Heering have challenged Heilbron's account, more particularly his emphasis on the role of grounding.[14] By replicating certain experiments with the Leiden jar they found that the jar could be charged without grounding.[15] This motivated them to revisit the original sources discussed by Heilbron. They show how in the first writings on the Leiden jar grounding was not the central concern. According to them, the significance of the early experiments with the jar lay in the development of the "conceptual idea of the electrical circuit."[16]

As we have seen, for Heilbron the significance of the Leiden jar for the history of electrical research lay in the fact that it was a theoretical anomaly and thus "forced a revolution in electrical theory."[17] Silva and Heering show that the early responses to and the experiments performed with the Leiden jar were however more diverse and should not be reduced to its treatment as a theoretical anomaly in need of an explanation. Certain researchers tried to replicate and stabilize the experiment. Others undertook a systematic analysis of the Leiden jar by experimental means, either to improve its working or to arrive at an explanation for the phenomenon. Finally, in some contexts the Leiden jar was used as a black box or piece of equipment to pursue other research aims, mostly of a medical nature.[18] Silva and Heering use Friedrich Steinle's concept of "exploratory experimentation" to describe this early experimental research on the Leiden jar.[19] According to Steinle, this type of experimentation typically takes place when no theoretical or conceptual tools are at hand to understand or explain the phenomenon under investigation. It often takes the form of a systematic variation of various experimental parameters, with the aim of discovering certain regularities.[20] We will see that van Musschenbroek's research on electricity also takes this form.

The manuscript material discussed in this article has never been subjected to a detailed discussion and is rarely referred to in the literature. The only exception that I am aware of is the work of Willem Dirk Hackmann on the history of the frictional electrical machine. However, Hackmann does not analyze the contents of the manuscript, nor does he spell out its implications for our understanding of van Musschenbroek's experiments. Moreover, his description of the content of the manuscript as "culminating with [van Musschenbroek's] discovery of the Leyden jar and [containing] experiments made with it as suggested by Nollet" does not, as we will see, do justice to the manuscript.[21]

Before turning to van Musschenbroek's manuscript, I will first discuss the chapters on electricity in the different editions of his textbook. Throughout his career as a university professor, van Musschenbroek published several editions of the textbook that he used for teaching. In this textbook, he provides his students and readers with a general overview of the state of the art of natural philosophy or physics (*physica*). More specifically, I will look at the editions published in the years before the first experiments with the Leiden jar. We will see how van Musschenbroek repeatedly emphasizes that not enough experimental results are available for a theoretical treatment of electricity to be possible. He therefore limits himself to providing an overview of the most important and salient experiments. This cautious approach towards theorizing and the emphasis on experimentation is characteristic of van Musschenbroek's general methodological views and research practice. These are also reflected in his own experimental research on electricity. Therefore, the next section helps to contextualize and understand the manuscript material discussed in this article.

Van Musschenbroek on electricity in his textbooks

Throughout his career as a university professor, van Musschenbroek published several editions of the textbook that he used for his courses on natural philosophy. The first edition, which appeared in 1729, did not contain a chapter on electricity. In the second edition, published in 1734, a separate chapter on electricity was added for the first time. The chapter begins with an outline of the "universal [operations] (*universalia*)" of electrical bodies.[22] Van Musschenbroek discusses electrical attraction, the types of bodies that can be subjected to it, the weather conditions that influence the operation of electricity, the types of substances that can and that cannot be penetrated by "electric effluvia," the types of substances that can communicate electricity, and the mutuality of electrical attraction.[23]

After this general overview, van Musschenbroek provides an outline of some experiments with a glass tube, taken over from Stephen Gray (1666-1736).[24] Van Musschenbroek simply provides an account of the experiments, without mentioning any (potential) explanation for the observed phenomena. He does not provide any references to established theories on the nature of electricity.[25] The passage immediately following the account of these experiments makes it clear why:

> We do not yet possess a sufficient supply of electrical experiments in order to accurately determine the nature, expulsion, return, movement, and subtlety of the electrical effluvia. Unless, [of course], we would indulge in conjectures, which [is something] a sober philosophy should always avoid.[26]

In 1736, van Musschenbroek published a Dutch translation of this textbook.[27] This was followed three years later by an expanded second edition.[28] The latter edition was in turn translated into French.[29] This French edition was praised by John Theophilus Desaguliers (1683-1744) in *A Dissertation Concerning*

Electricity as recommended literature for anyone interested in learning more about electricity.[30] The general organization of the chapter remained the same. Van Musschenbroek starts with a definition of electricity, gives a list of universal operations, and provides an overview of some experiments. The discussion of the *universalia* of electricity is expanded with additional facts, mainly derived from the work of Charles du Fay (1698-1739). Although du Fay at that point had already published about his discovery of the two electricities, van Musschenbroek does not discuss these findings in the 1736 edition.[31]

The list of experiments is also expanded with the dramatic signature experiments of Gray with suspended people or animals.[32] As in the 1734 edition, these experiments are presented as such and are not explicitly connected to theoretical considerations. Again, the discussion of these experiments is immediately followed by a remark on the relatively small amount of available experiments. The more expanded version of this remark in the Dutch edition makes it clear that van Musschenbroek thinks that more experiments are needed in order for a theoretical treatment of electricity to be possible:

> Many things will be hard to assess, because the [electric] exhalations are mixed, [coming] both from the body that rubs, as well as from the one that is being rubbed. But still these marvelous effects show that one only has to perform experiments in order to discover the miracles of nature. If as much progress is made every year, as we have witnessed recently through the diligence of the gentlemen Gray and Du Fay, we can hope, that we will soon be able to start reasoning, and to draw mathematical inferences from the phenomena, yes, to prove and explain everything.[33]

In the second edition of the Dutch textbook, several changes and additions were made. The overall structure of the chapter remained the same. Throughout, van Musschenbroek added further refinements, references to other experiments, and variations on experiments which had already been present in the previous edition. An example of a new experiment is an account of an experiment with a rotating glass, which precedes the list of experiments with the glass rod.[34] It is the first time this piece of apparatus finds its way into van Musschenbroek's textbooks. It will also be the apparatus used by van Musschenbroek in his own research. The list of experiments is again expanded with further observations made by Gray.[35] The last paragraphs of these more specifically deal with the phenomenon of electrical light.[36] Another important addition is a discussion of du Fay's discovery of the two kinds of electricity. In the preface, van Musschenbroek had already referred to this discovery. There, he had said that his own research had led him to believe that there is more than one kind of attractive force. To substantiate this, he emphasizes the distinction between conclusions that are arrived at through pure reasoning, and the often surprising (and complex) results of empirical research. The discovery of du Fay provides an example of this:

> Let everyone ask himself this: if he would have been [merely] thinking about the pulling force of bodies [in other words: electricity], would he then not state that there is only one such force? However, if we look at Nature herself, and see what the magnificent philosopher du Fay has discovered, we will learn that he has already found two types of electricity, namely the vitreous one and the resinous one. Who knows what more kinds [of electricity] [our] descendants will discover?[37]

The emphasis on the fact that nature often turns out to be more complex and heterogeneous than first expected is a recurrent theme in van Musschenbroek's writing.[38] We will see that this reoccurs in the manuscript material and also in van Musschenbroek's understanding of the Leiden jar.

The chapter on electricity in the 1739 Dutch textbooks ends with some general theoretical considerations. These are preceded by a lament on the lack of experiments, similar to the one found in the previous editions. Although he no longer claims that not enough experimental results are available, van Musschenbroek's remarks still have a strong agnostic flavor:

> Up until now, we have only enumerated the most important phenomena [exhibited by] electrical bodies. But we have not spoken about the causes of electricity, nor about its way of operating. Now would be the place to discuss this, so that we could clearly understand what has been said before. But oh, if only we would be able to do this! Caution teaches us not to proceed too rashly. This learning is still new. It has just begun and an infinite amount of things are required before one will be able to mathematically demonstrate everything, as I will soon show.[39]

But van Musschenbroek remains confident that if research keeps proceeding at the current rate, "we will soon discover the secret of electricity."[40]

The theoretical part of the chapter is organized as a series of questions. The first paragraph deals with the question of the relation between fire and electricity (§. 529).[41] Is electricity the same as common fire, is it something different but yet always accompanied by fire, or is it a different kind of fiery substance, etc. Already at the beginning of the paragraph, van Musschenbroek states that he "doubts whether at this point one can actually say something for certain about these questions."[42] He then provides arguments for different positions, in each case referring to relevant observations and experiments.[43] The next question is that of the exact relationship between the two kinds of electricity and the cause(s) of their difference (§. 530).[44] The last paragraphs deal with the question of the nature of the movement of the electrical effluvia (§§. 531-532). Van Musschenbroek thinks it is probable that they move in the form of vortices, but mentions that there are also counter-arguments to be found (§ 531).[45] The last question is what causes this vorticial movement (§. 532).[46]

The content of the chapter on electricity in the 1741 edition is quasi identical to that of the 1739 edition, although the text is more elaborate and detailed in the Dutch edition.[47] At the end of the chapter, a small comment is added:

> Until now nothing of all this has been demonstrated well. If someone will be able to put all these things in clear light, his name will deserve the token of eternal fame.[48]

Perhaps roused by his own words, four years after the publication of this edition van Musschenbroek will embark on a series of experiments on electricity. To these I will turn in the next section.

The Manuscript

The manuscript under discussion contains research notes from a specific period during which van Musschenbroek conducted experimental research on electricity.[49] The first note is dated on 10 December 1745 (fol. 63^{r}). The latest date encountered in the manuscript is 7 September 1746 (fol. 92^{v}). The notes thus coincide with the period during which van Musschenbroek performed his first experiment with the Leiden jar.[50]

The contents of the manuscript are not limited to experimental reports. One can discern four parts. The first part of the manuscript consists of a summary of opinions found in the literature on electricity, organized around a series of questions (fols 1^{r}-51^{r} and 54^{r}-61^{v}). The second part is a list of research questions and planned experiments (fols 52^{r}-53^{v} and fol. 62^{r-v}).[51] The third part contains the experimental reports (fols 63^{r}-94^{r}). The end of the manuscript consists of drafts for the chapter on electricity in the 1748 textbook (fols 96^{r}-104^{v}).[52] The collection of van Musschenbroek's manuscripts held at the Leiden University Library holds another manuscript which shows van Musschenbroek reusing earlier research notes to prepare a new edition of his textbook.[53] As I have mentioned at the beginning of this article, the manuscript has been neglected in the literature. The reason for this remains unclear. Most of the manuscript is written in Latin, with only a few passages written in Dutch. Van Musschenbroek's handwriting is also quite clear. One reason for the neglect might be the fact that the experimental reports are hidden between a summary of the literature on electricity and drafts for a chapter in van Musschenbroek's textbook. At first glance, the manuscript might appear as draft material for a new edition of the textbook, and would not suggest to its reader that it contains any material related to the discovery of the Leiden jar. Another possible reason is that the most complete and recent published overview of van Musschenbroek's manuscripts and their content is to be found in de Pater's monograph, which is written in Dutch. As such, getting information on van Musschenbroek's manuscript is difficult for a non-Dutch speaking audience.

The main subjects discussed in the first part of the manuscript can be summarized as follows: the question of which bodies are electric, questions related to the production of electricity and the factors influencing it, questions related to the operation of electric attraction and repulsion, which factors increase or decrease the electric force, the transmission of the electric force to other bodies, the movement of electricity, and the relation of electricity to light and fire.[54] Van Musschenbroek uses the scheme of research questions to organize results found in the literature.[55] At some places, we see that he also incorporates results from his own experiments, for example on the folium containing an overview of passages in the literature dealing with the question of how far the attractive force of electricity extends.[56] However, van Musschenbroek goes beyond just adding his own observations to a list of established results. The manuscript shows how van Musschenbroek uses his own experiments to comment on results or statements made by other authors.[57] At some places this leads him to propose further experiments.[58] The literature is also used to further reflect on the implications of the results obtained in his own research.[59]

This systematic overview and summary of the literature is followed by a list of proposals for future experiments.[60] Although no apparent order can be found in the list, the experiments can be linked back to the aforementioned research questions. In many cases, the experiments involve the variation of several components of the experimental set-up.

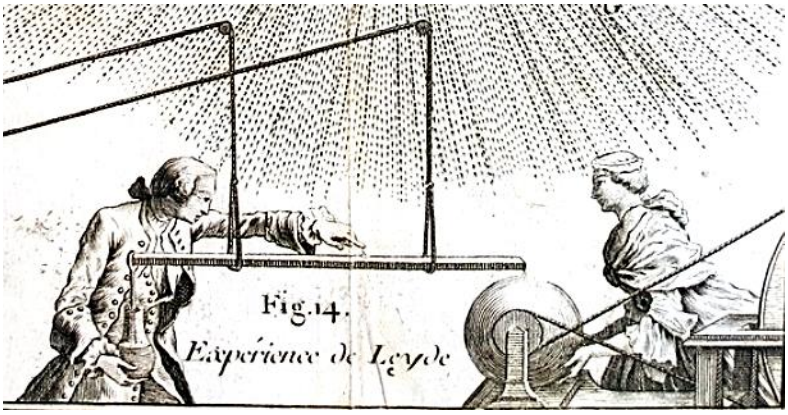

Fig. 1. Depiction of an experiment with the Leiden jar (Detail from Nollet, *Essai sur l'electricité des corps*, Pl. 4).

Before turning to a discussion of van Musschenbroek's research notes, it might be helpful to provide a short description of the experimental set-up used by van Musschenbroek. Although van Musschenbroek did not provide a detailed description, we can infer from the reports that he used the set-up that had been introduced into electrical research by either Georg Mathias Bose (1710-1761) or Christian August Hausen (1693-1743).[61] The figure (Fig. 1) depicting the experiment with the Leiden jar, taken from Jean-Antoine Nollet (1700-70)'s *Essai sur l'electricité des corps*, provides an image of this set-up.[62] At the right-hand side we see the glass globe, which is being turned by means of a wheel (only partly visible in the picture) and rubbed by the hands. To this globe, a metal bar (called "the prime conductor") is connected by means of threads (not depicted) hanging from the bar and touching the globe. The bar is hanging on (silk) ropes. This set-up can then be used to electrify materials by means of the prime conductor, or to draw sparks from the latter.

As this set-up consists of several elements, many ways of varying it present themselves. The person rubbing the globe with her hands can be replaced by a cushion, the prime conductor can be suspended with different materials, the machine and the persons doing the experiment can be made to stand on different materials (in different combinations), etc. The first experiments reported by van Musschenbroek, all dated on 10 December 1745, can be seen as a series of variations on this set-up. Van Musschenbroek started by varying the support of the iron tube. He first hung the tube on blue silk and bands of dishcloth. Then he varied the support of the tube, trying wreaths of camel hair, strings made from animal intestines, wands of seal-wax, and glass tubes from a barometer. The effect of the variation was tested by checking whether and how far from the tube a feather hanging on a wire was attracted by the tube, and by attempting to draw sparks from the iron tube.[63] The camel hair and gut-strings were found to be ineffective. The seal-wax wand and glass tubes both worked very well. By looking at the maximum distance from which the feather was attracted by the tube, van Musschenbroek obtained a numerical measure. In the next series of variations, van Musschenbroek let the iron tube rest on the glass tubes. Although no specific reason is mentioned for preferring the glass tubes over the seal-wax wands, a comparison of the numerical measure obtained in both experiments explains van Musschenbroek's choice. When seal-wax was used, the feather was drawn up to a distance of 12 inches from the iron tube, in the case of the glass tubes up to a distance of 16 inches.[64] Thus, when glass tubes were used, more electric force was produced, which explains van Musschenbroek's choice for these tubes in the following experiments.

At the end of his report on this first series of variations, van Musschenbroek states that "in these five experiments the globe had been rubbed with bare hands."[65] Having kept this variable fixed in the first five experiments, he now varied it in the following ones, keeping the others fixed (and using, as we have seen, the glass tubes as supports). Van Musschenbroek rubbed the globe with a series of different cushions. He tried a linen cushion filled with flax, a cotton cushion filled with cotton, a silk cushion filled with feathers, a silk cushion filled with horse hair, a leather cushion filled with feathers, an old black hat, and an unidentified type of skin.[66] In all cases, no or only a small amount of electricity was produced. Weather conditions were always lurking in the background as an uncontrollable variable. The experiments with the cushions provide a concrete example of this. The folium contains notes that were added later, which describe experiments made on 20 August 1746. On this day, the experiments succeeded well and van Musschenbroek was able to draw sparks from the iron tube.[67]

The next series of variations involved rubbing the cushion with different substances: chalk, minium, and starch.[68] The cushions produced more electricity when they were covered with chalk. When comparing the different types of cushions, van Musschenbroek notes, a very great amount of electricity was produced by the leather cushion rubbed with chalk. Even better results were obtained by using starch.[69]

The last experiment in the series consists in a variation on the connection between the glass globe and the iron tube. From the description of the experiment, we can infer that van Musschenbroek had previously used golden tassels for this.[70] He replaced these tassels by flax fibres and noticed that more electricity was produced. He therefore decided to no longer use the golden tassels.[71]

The only element of the set-up that was not varied was the support of the machine. However, the series of experiments made on the next day (11 December) end with an experiment in which the machine is put on stones. Van Musschenbroek does not observe any difference in comparison with putting the machine on wood.[72]

Although not explicitly labelled as such by van Musschenbroek, we can see the aforementioned series of experiments as a preliminary investigation of the elements of the experimental set-up. In an oration on the method of experimenting, delivered in 1730, van Musschenbroek had emphasized the importance of knowing one's apparatus and its possible flaws before conducting any experiment.[73] This first series of experiments can thus be seen to have the function of exploring and testing the experimental set-up itself.

Before turning to the experiments with the Leiden jar, the following general characteristics of van Musschenbroek's experiments on electricity can be mentioned.[74] One of the main characteristics of his experimental practice was that it consisted in the systematic variation of certain parameters, in order to observe the effects of these interventions. In the reports found in the manuscript, we see that van Musschenbroek used two means to observe the effects of his interventions. On the one hand, he used a feather hanging from a wire to see whether any pulling force was present. On the other hand, he tried to draw sparks with his hands. If either of one was observed, it meant that electricity had been produced. The sparks were also used as a qualitative measure of the electricity: the heavier the sparks, the more electricity there was.[75] The feather could also be used as a crude quantitative measure of the amount of electricity: the further away from the electrified body the feather was pulled, the more electricity.[76] In the experiments dealing with the nature of electric light, observations of the specific characteristics of the sparks played an important role.[77] Van Musschenbroek came to learn that electric phenomena depended on several variables (including the weather and the constitution of the air) that could not always be controlled. This led him to emphasize the importance of repeating the experiments. In the to-do list with experiments, a note reads: "All the phenomena should be examined at night, and during the day, and [the experiments] should be repeated often, because the circumstances differ."[78]

Let us now turn to the experiment with the Leiden jar. The experiment is part of a series of experiments dealing with the electrification of water. In experiment 21 (17 December), van Musschenbroek took a glass cylinder and filled it with water. Then he attached a copper wire of one foot long to the iron tube, and inserted the wire into the water. In this way he electrified the water. After 15 minutes, van Musschenbroek noticed a phosphorous smell. When drinking the water, he observed a small difference in taste. Van Musschenbroek also noticed the following:

> In the meantime the external surface of the glass vase strongly pulled a hanging feather, the upper part [of the vase] as strongly as the lower part. Hence, if the electric force did not run

along the surface of the water and the external surface of the glass vase, it will necessarily have gone through the water.[79]

Somewhat later, van Musschenbroek performed an experiment to determine “whether the electric force would go through the water” (experiment 29, 17 December).[80] To investigate this, van Musschenbroek connected a feather to a leaden stand in such a way that it stood upwards. The feather and stand were put in a glass vase which in turn stood on a box of resin. A bronze wire was hung from the iron tube, going into the glass vase. When electricity was produced, the wire could be seen to pull the feather. Then van Musschenbroek poured water in the vase until the surface of the water was one inch above the feather. When electricity was produced, the feather was no longer attracted by the wire. The surface of the water was however electric, and as in experiment 21, van Musschenbroek noticed that the complete exterior surface of the vase was electric as well. When he removed some water from the vase, so that the tip of the feather would touch the surface of the water, the feather was still not attracted by the wire. When he threw a small feather on the water it did float towards the wire. Based on these experiments, van Musschenbroek concluded “that the electric force does not go through the water but only runs along its surface.”[81] The next experiment (experiment 30) dealt with the effect of water on glass. Van Musschenbroek sprinkled the cushion that was used to rub the globe with water. When the globe was rubbed with this wet cushion, no electricity was produced. Van Musschenbroek concluded that “even if the glass surface is only slightly humidified, it prevents electric force to be incited.”[82]

The next experimental report (experiment 31) contains a description of an experiment with the Leiden jar:

> <u>31.</u> In this way we have discovered how much difference there is in [different types of] glass as to the electric force. I hung a copper wire of 1 feet long from the end of the iron tube, and ∨while standing on resin∨ I took a glass vase from which we are wont to drink beer. This [glass] was filled half with water. Then ∨the wire was hung in the middle of the water∨. When the globe was rotated, such heavy sparks were drawn from the wire to the finger that the pain was unbearable, and even the vase itself got cracks. The water remained electric for a long time and gave repeated explosions to the finger <the engravings on the external surface of the glass emitted bright, shining brushes. All the water was permeated by the light at each explosion>. This glass was Bohemian. I took other [specimen of] Bohemian glass, a lot [of them] showing the same effect. Next, I took British glass, but then no effect was seen: no spark, no cracking sound. It is necessary however that these drinking glasses stand on a box of resin, or are held in [one’s] hand, which is better than putting them on resin. However, when instead of water a precursor of spirit of wine was put in the vase, no such strong sparks struck [my] finger, because this kind of glass and water optimally oppose the electric forces: <the reason is not to be sought in the magnitude, form, or amplitude of the glasses, because both

> small and big, cylindrical and conical [glasses] produced [these] effects, and other similar [vases not made of glass] did not work. Porcelain vases did not work.>[83]

This passage provides the earliest written account by van Musschenbroek of his experiment with the Leiden jar.[84] Although he mentions that the pain of the spark was “unbearable,”~~,~~ he does not seem to have considered the experiment as important as it would later turn out to be.[85] The manuscript contains many comments on the experiment and reports of repetitions of the experiment, but these are all added later.[86] The report on the Leiden-jar experiment is immediately followed by a non-related experiment (experiment 32).[87]

At the beginning of his description of the experiment, van Musschenbroek makes it clear that the most salient finding from these experiments was the role of the glass. Through a series of variations he came to the conclusion that the specific strong sparks were only produced by means of Bohemian or German glass and that other variables were not relevant: “the reason is not to be sought in the magnitude, form, or amplitude of the glasses, because both small and big, cylindrical and conical [glasses] produced [these] effects, and other similar [things] did not influence [the outcome].”[88] Despite van Musschenbroek’s emphasis on the fact that German glass should be used, Nollet succeeded in producing the effect with French glass. According to Nollet, the type of glass was not a relevant variable. What is important is that the inner surface of the glass above the water line should be dry. He therefore concluded that van Musschenbroek was wrong in identifying the type of glass as the relevant factor, and that this conclusion was probably due to the fact that the German glass he was using was dry, whereas the English glass was humid.[89]

In the publication of the results of his experiments, Nollet also mentions his correspondence with Jean-Nicolas-Sébastien Allamand (1716-1787), who credits Cunaeus with the accidental discovery of the effect. Allamand described the experiment communicated by van Musschenbroek as a shared discovery and also mentioned experiments made by himself. [90] Note that in the passage from the manuscript cited above, van Musschenbroek writes: “*we* have discovered (*invenimus*).”[91] Although Nollet’s correspondence with Allamand confirms Heilbron’s suggestion that Cunaeus made the accidental discovery of the effect of the Leiden jar, the manuscript material does not substantiate Heilbron’s claim that only Cunaeus could have made this discovery because of his lack of a theoretical background. The experimental procedure is not described by van Musschenbroek as going against common practice, nor is it described as including a violation of a so-called rule. Moreover, as I will show shortly, van Musschenbroek does not treat the experiment as a theoretical anomaly, but rather as a confirmation of his views on the heterogeneity of electricity and the role of differences between types of glass in the production of electrical phenomena. Before turning to this issue, I should add that the manuscript material itself does not provide further information pertaining to the role of Cunaeus in the discovery. It is noteworthy that van Musschenbroek explicitly uses the first person plural, whereas in other reports he uses the first person singular.[92] Other passages in the manuscript further suggest that van

Musschenbroek had regular contacts with other people in Leiden performing their own experiments on electricity at the same time.[93]

Although Nollet's experiments demonstrated that the type of glass used was not a relevant variable in the Leiden jar experiment, van Musschenbroek continued to believe that in other cases, the nature of the glass would have an effect on the electric phenomena produced with it. In his 1748 textbook, a paragraph is devoted to the proposition that "not all idoëlectrics [the term then used for bodies which could be electrified by rubbing them] are equally generous" when it comes to producing electricity.[94] As an example, van Musschenbroek refers to different types of glass. The difference is due to the composition of the glass. Some types of glass contain more alkaline salt (*sal alcalinus*), whereas other types contain more metal calxes.[95] In the 1762 edition of the textbook, van Musschenbroek further adds that the production process also has an influence.[96]

Further textual evidence shows that van Musschenbroek was already convinced before the experiments with the Leiden jar that different types of glass produced different amounts of electricity. In Bose's *Tentamina electrica* of 1747, a letter from Samuel König (1712-1757) was included. In the letter, dated on 25 September 1745, König writes that he had been in Leiden with van Musschenbroek and that he had performed electrical experiments with him. More specifically, he mentions experiments in which they used a globe made from English glass with a diameter of 12 inches to incite electricity and with which they were able to set fire to spirit of wine.[97] Further in the letter, he writes that he and van Musschenbroek had the impression that the German glass that Bose was using for his experiments worked better than the English glass they were using themselves.[98]

But glass is not the only material that van Musschenbroek considers as relevant. On the basis of another variation upon the experiment, water is also taken to be a necessary component for its success. When a precursor of spirit of wine was used instead of water, the effect failed to be produced. Because of this emphasis on the role of water and glass, the Leiden jar experiment clearly fits in the series of other experiments we have discussed (experiments 21, 29, 30). In the passage from the manuscript cited above, van Musschenbroek moreover seems to suggest that there is something specific about the combination of water and glass which gives rise to the phenomenon of the Leiden jar: "because this kind of glass and water optimally oppose the electric forces."[99]

In a comment on one of his earlier experiments (experiment 9 in the manuscript), van Musschenbroek criticizes Winkler for stating that the electric matter belongs particularly to electric bodies. Van Musschenbroek links this to the heterogeneous nature of electricity. In this comment, he explicitly connects these views with the issue of the nature of glass:

> I do not see why this would follow, because electricity could be something composed out of various parts, of which some are in the air, others are in bodies, [and] which simultaneously approach one another and get mixed, and [thus] produce that composite, which is electric.

> Therefore it can be that from bodies that are not in themselves an electric, something nonetheless flies out, which has to be mixed with the former, so that from these three coming together electricity arises: & perhaps several need to be in the air [at the same time?], which can run together. And if too much [matter] of one kind should rush in, it gives rise to an electric matter with different forces, so that if too much fire would rush in, the electricity is weaker, if too little fire would be present, the electricity is also weaker. And because of this, different kinds of glass, which emit different exhalations, give rise to differences in electricity. There are [types of glass] that have no electricity because they do not exhale those [particles] which by their coming together with fire and other [types of matter] give rise to electric matter.[100]

Other passages in the manuscript suggest that van Musschenbroek was inclined to think that electricity was in fact a heterogeneous substance. In the list of research questions, van Musschenbroek listed as one of the research questions: "<u>20</u> Isn't the electric force a composite? How to separate it from fire?"[101] Elsewhere in the manuscript, we also find a passage in which van Musschenbroek provides a lists of arguments for the proposition that "<u>Electricity</u> is a matter composed of different parts that come together."[102] A bit further in the manuscript, a loose note is inserted with further arguments that should be added to this list. The fact that one cannot incite electricity with certain types of glass is one of these additions. The passage reads as follows:

> There are [types of] glass that are incapable of [generating] electricity, even when people who are [otherwise] good at generating electricity would be rubbing that specific glass. Therefore certain dispositions of the glass and of the rubbing substances need to concur.[103]

Van Musschenbroek could be expected to be sympathetic towards the idea that electricity is a heterogeneous substance. Recall that in the preface to the second edition of his Dutch textbook, he had singled out du Fay's discovery of the two electricities as an example of the way in which empirical findings often go against rationalistic attempts to reduce nature to a very limited set of principles. The emphasis on the heterogeneity of nature and the related warning against relying too much on simplified and abstract notions are a recurrent theme in van Musschenbroek's writing.[104] Therefore, it is not surprising that after referring to du Fay's discovery, he asked his readers: "Who knows what more kinds [of electricity] [our] descendants will discover?" In the 1748 edition of the textbook, the position that electricity "is not some homogeneous fluid, but consists of different substances that are mixed together" is mentioned as a fact that can be inferred from experiments.[105]

Van Musschenbroek's views on the heterogeneity of electricity and his related views on experimentation help to explain his response to the Leiden jar. Before turning to this, it might be helpful to provide a short discussion of the implications of the manuscript material for our current understanding of the early history of the Leiden jar, as discussed above. Of course, the material only provides us with information on van Musschenbroek's individual reaction to the discovery. Nonetheless, the manuscript material further substantiates Silva and Heering's criticism of Heilbron's take on the matter. As we have seen, according to Heilbron it is likely that Cunaeus and not van Musschenbroek "discovered" the Leiden jar and that this discovery was of an accidental nature, due to the fact that Cunaeus was unaware of "Dufay's Rule" and therefore forgot to insulate the jar. According to this interpretation, the necessity of grounding the jar formed the most salient aspect of the new phenomenon. Moreover, the fact that the Leiden jar clearly violated the well-established rule of Dufay made it into a theoretical anomaly. Silva and Heering have argued however that contemporary accounts did not in fact emphasize the necessity of grounding the jar and did not consider it to be the most salient feature of the new discovery. They further note that from van Musschenbroek's letter to Réaumur, in which the discovery is communicated, "the reader [...] might not get the impression that something spectacular is communicated."[106] The passage in the letter dealing with the discovery begins with van Musschenbroek remarking that since he has a little bit of space left on the sheet of paper he might as well tell the story of a recent "new but terrible" experiment.[107] Nothing in the letter suggests that van Musschenbroek thought of the experiment as an anomaly.

From the account found in the manuscript, one also gets the impression that, aside from the strength of the shock, van Musschenbroek was not that impressed or surprised by the experiment. As we have seen, in the manuscript the account of the experiment with the Leiden jar is immediately followed by another, unrelated experiment. This is not the reaction one would expect from an experimentalist confronted with a fundamental theoretical anomaly. The manuscript does contain further material in which repetitions and variations on the experiment are mentioned, but these are all inserted later and include references to debates in the literature.[108] They are thus only added after the Leiden jar had already become a topic of discussion in the learned world. The manuscript also further confirms Silva and Heering's criticism of Heilbron's views on the importance of the necessity of grounding the jar. In the account of the experiment cited above, van Musschenbroek does not state that grounding is necessary. On the contrary: he writes that he was standing on resin and was thus insulated. Near the end of the account he even explicitly says that "it is necessary however that these drinking glasses stand on a box of resin (*capsulae picis*) or are held in one's hand, which is better than putting them on resin." Even though holding the jar in one's hand is mentioned as being better than putting it on resin, van Musschenbroek nowhere suggests that this is an unexpected or anomalous aspect of the phenomenon. Moreover, the necessity of grounding is not mentioned. The formulation leaves open the possibility that the person holding the jar in one's hand is standing on resin himself (as van Musschenbroek himself was doing according to the report), so the remark cannot even be taken as an indirect reference to the importance of grounding the jar. In a letter written to Bose (and later published by Bose in his 1747 *Tentamina electrica*), dated on 20 april 1746, van Musschenbroek gives an account of the experiment and adds that he has tried the experiment in different ways with the same "violent effect." He explicitly states that the experiment worked both when standing on resin or when standing on the floor.[109]

In the same letter, van Musschenbroek complains about the unfavorable weather conditions in Holland when it comes to performing electrical experiments. He therefore asks Bose to perform certain experiments in the more favorable conditions provided by the German climate and its drier air. In this way, it could be excluded that certain experiments merely failed because of the unfavourable humid air in Holland. As we have seen, Heilbron did not have a very positive assessment of van Musschenbroek as an experimentalist. According to him, "the Leyden professor was not, in fact, a very imaginative electrician."[110] With regard to the experiments proposed by van Musschenbroek, Heilbron adds in a footnote:

> In connection with Musschenbroek's unimaginative approach to the study of electricity, it is interesting that almost all the investigations contemplated here involved varying well-known experiments by using many different kinds of materials.[111]

What Heilbron fails to appreciate however is that this activity of systematically varying the materials used in the experiments is a characteristic of van Musschenbroek's general practice of experimenting and is motivated by clear methodological views. A central theme therein is the importance of avoiding hasty generalizations.[112] On an experimental level, this means that one must repeat an experiment in different circumstances and with different substances (if possible) before one can be certain to have found an empirical regularity. In the last edition of his textbook, van Musschenbroek links this practice of varying experiments to the discovery of the differences between types of glass when it comes to their production of electricity:

> These kinds of varying outcomes can only be discovered by one who is constantly occupied with making and repeating experiments, and who is not satisfied with exploring one kind of bodies.[113]

In the letter to Bose, van Musschenbroek explicitly links the necessity of varying the experimental set-up to his views on the heterogeneity of electricity:

> I have only opened the field, in which we are to proceed by means of induction, or by [investigating every] single body, in order to learn, that electricity is a substance composed of several exhalations coming together, of which some are more copiously present in this [body], and more sparingly [present] in other bodies. If we would make haste, and draw general conclusions from very little observations, we will immediately be prone to error.[114]

This brings us back to the issue of van Musschenbroek's views on the heterogeneity of electricity and his initial reactions to the phenomenon of the Leiden jar. As we have seen, in the manuscript notes dealing with the heterogeneity of electricity, van Musschenbroek mentioned the fact that some types of glass do not generate electricity, even when they are rubbed in a way that has proven to be successful in other contexts. This was because "certain dispositions of the glass and of the rubbing substances need to concur."[115] At the beginning of the report on the Leiden jar experiment, van Musschenbroek writes that the experiment taught him “how much difference there is in [different types of] glass as to the electric force.”[116] After mentioning the variations performed on the experimental set-up, by using different types of glass and different fluids to fill the jar, van Musschenbroek concluded that only the specific combination of German glass and water worked so well “because this kind of glass and water optimally oppose the electric forces.”[117] The salient feature of this experiment for van Musschenbroek was thus the combination of two very specific types of materials leading to a very heavy shock. Given his belief in the heterogeneity of electricity and the fact that it arises from a combination of substances coming from different bodies, the logical next investigative step would be to further vary both the container as well as the contents of the jar in order to see whether another combination of materials would generate a comparable or even a greater shock. And this is indeed what van Musschenbroek suggests as the next step, both in the manuscript and in the letter to Bose. In the manuscript, we find the following added note:

> Try this experiment by putting a bronze, or iron, or golden wire in spirit of wine, spirit of sal ammoniac, spirit of salt, in oil of vitriol, oil of tartar *per deliquium*, in purified oil of turpentine, in another purified oil, in petroleum, in spirit of nitre, in milk, in blood, in urine, in bile, in oil of whales, in mercury, in other words: in every kind of fluid, and put the vase on metal, or on wood, or on resin, or metal on resin, and explore the magnitude of the blow by means of a metal globe hanging from a long metal wire, [by seeing] to which distance it is projected, by the method of Guljelmini.[118]

The salient feature for van Musschenbroek is clearly the magnitude of the shock and the matter to be investigated is which combination of parameters results in such a shock. Also note that this passage further confirms that the necessity of grounding the jar was not seen as a salient feature of the experiment. The variations include putting the jar on resin, that is, insulating it. In a letter written to Bose on 20 October 1747, van Musschenbroek again asks Bose to perform certain experiments in the more favorable German climate and proposes a series of variations on the contents of the jar. Again, the matter to be observed is the magnitude of the blow.[119] These passages also show that van Musschenbroek’s practice of varying an experiment by using different kinds of materials is not, as Heilbron suggests, “unimaginative” or a mere curiosity.

Conclusion

In this article, I have discussed manuscript material written by van Musschenbroek related to his first experiments with the Leiden jar. In order to contextualize the passages dealing with the Leiden jar, I have discussed the chapters dealing with electricity in the textbooks that van Musschenbroek published in the years before he conducted his experiments. We have seen how van Musschenbroek shied away from providing a theoretical explanation for the known phenomena related to electricity, choosing instead to provide an overview of experimental results. Not enough experiments had been performed, according to van Musschenbroek, for a theoretical treatment of the phenomenon of electricity to be possible. I further provided a general characterization of the nature of van Musschenbroek’s research on electricity. Van Musschenbroek’s research can be seen as an example of what Friedrich Steinle has called “exploratory experimentation”. According to Steinle, this type of experimentation is often performed in periods or fields where a theoretical framework is not (yet) present. It takes the form of a systematic variation of experimental parameters, with the aim of identifying certain regularities. We have seen how van Musschenbroek started his experimental research with an investigation of the standard experimental set-up itself, by varying the parts of the set-up and observing the effect on the amount of electricity that was produced. This was also how van Musschenbroek suggested to proceed after having performed the first experiment with the Leiden jar: varying the several components of the apparatus and observing how it affects the magnitude of the shock.

The manuscript material further confirmed the recent work by Silva and Heering on the early history of the Leiden jar. Silva and Heering argued contra Heilbron that the necessity of grounding the jar was not seen as the most striking feature of the Leiden jar by the historical actors themselves. In van Musschenbroek’s manuscripts, we likewise found no mention of the necessity of grounding the jar. On the contrary, we even found certain passages in which the description of the experiment clearly implied that the jar had been insulated. According to Heilbron, the Leiden jar formed a severe theoretical anomaly and was recognized as such by the electricians at the time. In the manuscript however, van Musschenbroek nowhere seems to suggests that the Leiden jar poses a problem for existing theories on electricity. On the contrary, from the material discussed in this article, one gets the impression that van Musschenbroek instead saw the phenomenon of the jar as a confirmation of his belief in the heterogeneous nature of electricity. We have seen how the manuscript material suggested that, contrary to the agnostic stance professed in his earlier textbooks, van Musschenbroek was committed to the idea that electricity was a heterogeneous substance and that electrical effects were produced by the combination of different substances coming from different types of materials. The nature and the strength of the effect depended on the specific materials being combined. The fact that only very specific combinations of substances seemed to produce the shocking effect of the Leiden jar was thus to be expected.

The manuscript did not provide any further information on the role played by Cunaeus in the discovery of the Leiden jar. However, as we have seen, Nollet mentioned a correspondence with Allamand in which the latter credited Cunaeus with the accidental discovery of the effect. Nonetheless, the manuscript material did not substantiate the claim that Cunaeus discovered the effect due to his amateurship. The passage in the manuscript dealing with the Leiden jar is special in the sense that the account is given in the first person plural, whereas other experiments are reported in the first person singular. This on the one hand confirms the idea that the discovery of the Leiden jar was seen as a “group effort,” but on the other hand also shows that van Musschenbroek incorporated this result in an experimental program that he mostly performed individually. He did however regularly communicate with other individual experimenters performing research in Leiden. In recent literature, eighteenth century electrical experiments have often been discussed in relation to their public character, especially their use as entertaining demonstration experiments. Other literature has pointed at the more general cultural impact of electrical experiments and theory and its relation to Enlightenment culture and politics.[120] These are of course important aspects of the role of electrical experiments in eighteenth century culture. However, the manuscript material under discussion invites us to revive our interest in eighteenth century electrical experiments that were performed by natural philosopher as part of a research program.

The manuscript material also helped to rectify the picture painted by Heilbron of van Musschenbroek's experimental program in electricity. Rather than "unimaginatively" repeating and varying existing experiments and stumbling upon the experiment with the Leiden jar, van Musschenbroek performed a series of experiments with a certain systematicity. We characterized his research as an example of what Steinle calls "exploratory experimentation". Steinle introduced this concept to provide an alternative to the "standard view" on experimentation according to which experimentation is always theory-driven.[121] Despite Heilbron's attention to the experimental side of eighteenth-century electrical experimentation, his overview of the history of electricity in the seventeenth and eighteenth century mainly reads as a history of *theories* on electricity and as a painstaking process of random experimentation, in the end leading to the development of the necessary concepts to provide the basis for a quantitative treatment of the phenomenon of electricity.[122] This theory-centered approach might also help explain Heilbron's negative assessment of van Musschenbroek's experimental work.

Steinle has also used the concept of "exploratory experimentation" to analyze the work of Charles du Fay. He shows how, despite the absence of a clear theoretical framework, du Fay's experimental research had a certain systematicity, and in the end led to conceptual innovation, specifically the concepts of "resinous" and "vitreous" electricity.[123] In this article, I hope to have given reasons for a similar renewal of appreciation for van Musschenbroek's experimental work on electricity and its systematicity. Taken together, the experimental programs of du Fay and van Musschenbroek demonstrate that there is more to the history of eighteenth century electricity than the succession of theories devised by academic philosophers on the one hand, and the spectacular demonstration experiments which were fashionable among an "amateur" audience, on the other hand. As such, my analysis opens the way to further research complementing existing accounts with a detailed assessment of the research performed by eighteenth-century experimentalists.

As I have mentioned, a lot of material concerning developments related to the Leiden jar was added to the manuscript. Further research therefore needs to be done, which promises to provide more information on how van Musschenbroek reacted to these new findings and which will in general contribute to our understanding of the early history of the Leiden jar. Due to lack of space and the complexities involved in dating the notes, I have refrained from discussing this added material. Therefore, to cite van Musschenbroek's letter to Bose, "I have only opened the field." Nonetheless, I hope to have provided a small contribution to our knowledge of the history of the Leiden jar.

Notes

[1] Once the news of the discovery spread, many experimenters tried to replicate and further explored the Leiden jar. Attempts were also made to provide a theoretical explanation for the phenomenon. Both van Musschenbroek's manuscript and the later editions of his textbook testify to his continued engagement with these developments. This however lies beyond the scope of the current paper. For a transcription and translation of these manuscript passages, including the ones discussed in this paper, see the appendix in Pieter Present, *Learning in the World: Petrus van Musschenbroek (1692-1761) and '(Newtonian) Experimental Philosophy'* (Brussels: VUBPress, 2019). It should also be noted that Ewald Jürgen von Kleist (1700-1748) had already discovered the phenomenon in October 1745 (John L. Heilbron, *Electricity in the 17th and 18th Centuries: A Study of Early Modern Physics* (Berkeley/Los Angeles/London: University of California Press, 1979), p. 311). Kleist communicated his results through letters, but his correspondents had difficulty replicating the experiments. Van Musschenbroek's discovery is generally taken to be an independent, parallel discovery (Cibelle Celestino Silva and Peter Heering, "Re-Examining the Early History of the Leiden Jar: Stabilization and Variation in Transforming a Phenomenon into a Fact," *History of Science* 56, no. 3 (2018): 314-52, 315-317).

[2] Present, *Learning in the world*, p. 222 (note 1).

[3] Van Muschenbroek's letter can be consulted online: "To Benjamin Franklin from Pieter van Musschenbroek, 15 April 1759," *Founders Online,* National Archives, <https://founders.archives.gov/documents/Franklin/01-08-02-0091>. The page is a digital version of the following original published source: Leonard W. Labaree (ed.), *The Papers of Benjamin Franklin*, vol. 8 (April 1, 1758, through December 31, 1759) (New Haven and London: Yale University Press, 1965), pp. 329–33.

[4] John L. Heilbron, "G. M. Bose: The Prime Mover in the Invention of the Leyden Jar?" *Isis* 57, no. 2 (1966): 264-7, 264.

[5] Heilbron, "G.M. Bose," 265 (note 4).

[6] Cibelle Celestino Silva and Peter Heering, "Re-Examining the Early History of the Leiden Jar: Stabilization and Variation in Transforming a Phenomenon into a Fact" (note 1).

[7] Cornelis de Pater, *Petrus van Musschenbroek (1692-1761), Een Newtoniaans Natuuronderzoeker* (Utrecht: Elinkwijk, 1979). This work also contains a helpful overview of all of van Musschenbroek's manuscripts. Again, this is to date the most complete published overview of these manuscripts. Unfortunately, this work is only available in Dutch. A short summary of de Pater's take on van Musschenbroek can be found in Kees (Cornelis) de Pater, "'The Wisest Man to Whom This Earth Has as Yet Given Birth': Petrus van Musschenbroek and the Limits of Newtonianism," in *Newton and the Netherlands*, ed. Eric Jorink and Ad Maas (Amsterdam: Leiden University Press, 2012), pp. 139–53. The research presented here has benefitted a lot from de Pater's pioneering work, especially his overview of the manuscripts. However, the same overview again demonstrates the relative neglect of the manuscript on electricity. De Pater's description of the manuscript discussed in this article only reads: "This manuscript contains a collection of electrical experiments (*Dit ms. geeft een verzameling elektrische proeven*)" (de

Pater, *Petrus van Musschenbroek*, p. 363). I will say more about the possible reasons for the neglect of this manuscript further in the article.

[8] Heilbron, "G.M. Bose," 266 (note 4).

[9] Heilbron, "G.M. Bose," 265-6 (note 4).

[10] Heilbron, *Electricity*, p. 253 (note 1).

[11] Heilbron, *Electricity*, p. 253 (note 1). The term "electric" was used to refer to bodies which could be easily electrified by rubbing them, such as glass or wax. "Nonelectric" bodies included wood and metals (Heilbron, *Electricity*, p. 253 (note 1)).

[12] Heilbron, *Electricity*, p. 253 (note 1).

[13] Heilbron, "G.M. Bose," 267 (note 4).

[14] Silva and Heering, "Re-Examining the Early History of the Leiden Jar," 314–52 (note 1).

[15] Silva and Heering, "Re-Examining the Early History of the Leiden Jar," 5-6 (note 1).

[16] Silva and Heering, "Re-Examining the Early History of the Leiden Jar," 24 (note 1).

[17] Heilbron, *Electricity*, p. 253 (note 1).

[18] Silva and Heering, "Re-Examining the Early History of the Leiden Jar," 24-8 (note 1).

[19] Silva and Heering, "Re-Examining the Early History of the Leiden Jar," 28 (note 1).

[20] Friedrich Steinle, "Entering New Fields: Exploratory Uses of Experimentation," *Philosophy of Science* 64 (1997): S65–S74; Friedrich Steinle, "Experiments in History and Philosophy of Science," *Perspectives on Science* 10, no. 4 (2002): 408–32.

[21] Willem Dirk Hackmann, *Electricity from Glass: The History of the Frictional Electrical Machine, 1600-1850* (Alphen aan den Rijn: Sijthoff & Noordhoff, 1978).

[22] Petrus van Musschenbroek, *Elementa physicae conscripta in usus academicos* (Leiden: Samuel Luchtmans, 1734), p. 137.

[23] Van Musschenbroek, *Elementa physicae* (1734), p. 135–7 (note 22).

[24] He mentions that the experiments "have been discovered and described by Gray, more elaborately than the way in which they are discussed in this compendium. A few [of them], which we show in the auditorium, should be noted" (van Musschenbroek, *Elementa physicae* (1734), p. 137) (note 22)). Unless noted otherwise, all translations provided in this article are my own.

[25] Van Musschenbroek, *Elementa physicae* (1734), p. 137–8 (note 22).

[26] Van Musschenbroek, *Elementa physica* (1734), p. 138 (note 22).

[27] Petrus van Musschenbroek, *Beginselen der natuurkunde beschreeven ten dienste der landgenooten* (Leiden: Samuel Luchtmans, 1736).

[28] Petrus van Musschenbroek, *Beginsels der natuurkunde beschreeven ten dienste der landgenooten* (Leiden: Samuel Luchtmans, 1739).

[29] Petrus van Musschenbroek, *Essai de physique*, trans. Pierre Massuet (Leiden: Samuel Lugtmans, 1739).

[30] John Theophilus Desaguliers, *A Dissertation Concerning Electricity* (London: W. Innys and T. Longman., 1742), p. 46.

[31] He will do so for the first time in the next Dutch edition of 1739, which I discuss below.

[32] Van Musschenbroek, *Beginselen*, pp. 258–9 (note 27).

[33] Van Musschenbroek, *Beginselen*, p. 259 (note 27).

[34] Van Musschenbroek, *Beginsels*, p. 270 (note 28).

[35] Van Musschenbroek, *Beginsels*, pp. 274–5 (note 28).

[36] Van Musschenbroek, *Beginsels*, pp. 275–6 (note 28).

[37] Van Musschenbroek, *Beginsels*, Unnumbered preface.

[38] For an elaborate discussion, see Present, *Learning in the world*, pp. 43-94 (note 1).

[39] Van Musschenbroek, *Beginsels*, p. 277 (note 28).

[40] Van Musschenbroek, *Beginsels*, p. 277 (note 28).

[41] Van Musschenbroek, *Beginsels*, p. 277–8 (note 28).

[42] Van Musschenbroek, *Beginsels*, p. 277 (note 28).

[43] Van Musschenbroek, *Beginsels*, p. 27-8 (note 28).

[44] Van Musschenbroek, *Beginsels*, p. 278 (note 28).

[45] Van Musschenbroek, *Beginsels*, p. 278–9 (note 28).

[46] Van Musschenbroek, *Beginsels*, p. 279 (note 28).

[47] A good example of this is provided by §. 472 in the 1741 edition (Petrus van Musschenbroek, *Elementa physicae conscriptae in usus academicos* (Leiden: Samuel Luchtmans, 1741), p. 176). In the Latin edition, this passage consists of a small paragraph, in the Dutch edition (§. 505) it is an elaborate description of more than a page long of experiments made by du Fay and Gray (van Musschenbroek, *Beginsels*, pp. 268–9 (note 28)).

[48] Van Musschenbroek, *Elementa physicae* (1741), p. 182 (note 47).

[49] MS Leiden University Library, Special Collections, Bibliotheca Publica Latina (henceforth LUL BPL), Item 240, part 18 (henceforth 240.18). In what follows, all translations of the manuscript material are my own. I will not provide a transcription of the original Latin (or Dutch). A transcription of most of the passages discussed in this article can be found in Present, *Learning in the world*, pp. 249-85 (note 1).

[50] Van Musschenbroek's first communication on this discovery was in a letter to Réaumur, dated 20 January 1746 (Heilbron, *Electricity*, p. 314 (note 1)).

[51] Loose notes containing ideas for further experiments are found on fol. 105^r and fol. 106^r.

[52] The reference for this edition of the textbook is: Petrus van Musschenbroek, *Institutiones physicae conscriptae in usus academicos* (Leiden: Samuel Luchtmans et filius, 1748).

[53] MS LUL BPL 240.29, which contains reports on experiments on the strength of materials. For a discussion of this research and its incorporation into the textbook, see Present, *Learning in the world*, pp. 118-30 (note 1)).

[54] For an overview of the topics discussed in the first part, see Present, *Learning in the world*, p. 241 (note 1).

[55] The authors that are referred to the most, are: Johann Heinrich Winkler, William Watson, Johann Gabriel Doppelmayr, Jacob Sigismund von Waitz, Christian Gottlieb Kratzenstein, Johann Gottlob Krüger, Georg Mathias Bose. Also referred to several times (but less frequently) are Jean Théophile Desaguliers, Jean Antoine Nollet, and Christian August Hausen.

[56] LUL BPL 240.18, fol. 37^r (note 49). The references are to an experiment made on 21 December 1745, and to one made in July 1746.

[57] For example, in a passage dealing with the question whether electricity can move through bodies, van Musschenbroek writes that Andreas Gordon is of the opinion that electricity cannot pass easily through glass, but adds that he believes Gordon is mistaken, because he has experimental evidence showing the contrary (LUL BPL

240.18, fol. 28r (note 49)). The passage referred to can be found in Andreas Gordon, *Versuch einer Erklärung von den Ursachen der Electricität* (Breslau: Verlegts Johann Jacob Korn, 1745), p. 45.

[58] For example, in a passage dealing with the augmentation of the electric force, van Musschenbroek writes: "Kratzenstein says in § 36 of his *Theor. Electr.*, pag. 13 that if one wants to confer the greatest electric force to bodies, …, the machines themselves, along with the turners and the people rubbing [the globe], should be put on resin. Test [this], because it is undoubtedly wrong." (LUL BPL 240.18, fol. 22r (note 49)) In the list of experiments to be made, found further in the manuscript, van Musschenbroek included: "8° To put everything on pitched planks." (LUL BPL 240.18, fol. 52v (note 49)) This probably refers to the same experiment. Kratzenstein provided further inspiration for experiments. On the same folium on the augmentation of the electric force, van Musschenbroek writes: "[Kratzenstein] further says on page 13, article 5, that bodies are less electric, the bigger their specific weight is, and the bigger the ratio between their surface and their mass is. Therefore, electricity can more strongly be conferred to them, and therefore they are more heavily attracted by electrified [bodies]. Repeat with tin and lead rods and see whether there is a difference." (LUL BPL 240.18, fol. 23r (note 49)) The passage referred to can be found in Christian Gottlieb Kratzenstein, *Theoria electricitatis more geometrico explicata* (Halle: Impensis Caroli Hermanni Hemmerde, 1746), p. 13.

[59] On fol. 58r for example we read remarks on experiment 58 (the report of which can be found on fols 79v-80v), the results of which are compared to Bose's views.

[60] The lists contains 54 numbered research questions. Numbers 1-38 are found on fols 52r-53v, numbers 39-54 are found on fol. 62r-v. A transcription and translation of these research questions can be found in Present, *Learning in the world*, pp. 242-8 (note 1).

[61] According to Heilbron, it is unclear who should be credited with introducing this set-up into electrical research (Heilbron, *Electricity*, p. 263-71 (note 1)).

[62] Jean-Antoine Nollet, *Essai sur l'electricité des corps* (Paris: Chez les freres Guerin, 1746).

[63] Experiments 1-5 (LUL BPL 240.18, fol. 63r-v (note 49)). This procedure was used by van Musschenbroek throughout his research on electricity as a means of measuring the electricity.

[64] Experiments 4 and 5 (LUL BPL 240.18, fol. 63v (note 49)).

[65] LUL BPL 240.18, fol. 63v (note 49))

[66] Experiments 6 and 7 (LUL BPL 240.18, fol. 64r (note 49)). The unidentified type is mentioned in an added note on an experiment made on 20 August 1746: "Cum pelle ex Cauda Maters" (ibid.). For the experiments with the cotton cushion, van Musschenbroek performed some more variations on the set-up: "I held the cushion in my hand, held the wand, I stood on laths, then I stood on resin, but no electric force could be observed, because not even the feather was moved." (LUL BPL 240.18, fol. 64r (note 49)) This series of variations was not performed for the other cushions.

[67] LUL BPL 240.18, Fol. 64r (note 49))

[68] Experiments 8 and 9 (LUL BPL 240.18, fol. 64v (note 49)) The minium (also known as red lead) was only used on a leather cushion, to compare its effect to that of chalk.

[69] "Starch is the best of all [means] to incite electric force." (LUL BPL 240.18, fol. 64v (note 49)) This is inferred from the fact that when he used a leather cushion rubbed with starch, van Musschenbroek "drew better and more abundant sparks, than when [his] wife rubbed the globe with her hand ∨after chalk had been applied∨." (LUL BPL 240.18, fol. 64v) Apparently, the hands of van Musschenbroek's wife were so good at producing electricity that

they were used as a measure. In 1738, van Musschenbroek had married his second wife, Helena Astorphius (1692-1760), six years after the death of his first wife, Adriana van de Water (1694-1732) (de Pater, *Petrus van Musschenbroek*, p. 27 (note 7)). It is thus Helena Astorphius who assisted van Musschenbroek with these experiments.

[70] Experiment 10 (LUL BPL 240.18, fol. 68^{r} (note 49)). Van Musschenbroek uses the Dutch term "goude franje". He does not give a description of these. From the list of research questions we can infer that these were probably made from gilt silk: "6° To hang tassels made from cither-wire or iron clavichord strings around the hollow pipe or iron rod, and see whether this is better than golden tassels, which contain silk" (LUL BPL 240.18, fol. 52^{r} (note 49)).

[71] LUL BPL 240.18, fol. 68^{r} (note 49). Van Musschenbroek describes an experiment with the finger of a glove, which also produces better results. He surmises that it might be better than using flax, but for some reason does not decide to opt for the use of leather.

[72] Experiment 15 (LUL BPL 240.18, fol. 68^{v} (note 49)). Experiment 14 might also be seen as a variation upon the iron tube, which was replaced by an iron rod. Again no difference was observed (ibid.). In experiments 41 and 42 (20 December), variations were made on the support of the machine (LUL BPL 240.18, fols 76^{r}-78^{r} (note 49)). However, these were not variations to test the set-up itself but variations made in order to demonstrate that the electric force ascended from the floor through the machine. This investigation should be seen in the context of the discovery that insulating the operator and the instrument led to less electricity being produced, contrary to expectations. It had been expected that more electricity would be produced, as the wax or resin would prevent electricity from flowing away into the ground. In his discussion of this episode, Heilbron mentions Allamand as one of the discoverers of this effect, along with Bose, Watson, Wilson, and Franklin. Allamand did not attempt to explain this episode, whereas Watson, Wilson and Franklin concluded that this meant that the electricity ascended from the ground (Heilbron, *Electricity*, p. 299 (note 1)).

[73] For a discussion of this oration specifically, and van Musschenbroek's methodological views more generally, see Present, *Learning in the world*, pp. 81-94 (note 1).

[74] For a more elaborate discussion, see Present, *Learning in the world*, pp. 151-78 (note 1).

[75] See for example experiments 6-8 (LUL BPL 240.18, fol. 64^{r-v} (note 49)).

[76] See for example experiments 1-5 (LUL BPL 240.18, fol. 63^{r-v} (note 49)).

[77] See for example experiment 23 and the note on this experiment (LUL BPL 240.18, fol. 70^{r-v} (note 49)).

[78] LUL BPL 240.18, fol. 62^{v} (note 49).

[79] LUL BPL 240.18, fol. 69^{v} (note 49).

[80] LUL BPL 240.18, fol. 73^{v} (note 49).

[81] LUL BPL 240.18, fol. 74^{r} (note 49).

[82] LUL BPL 240.18, fol. 74^{r} (note 49).

[83] LUL BPL 240.18, fol. 74^{r-v} (note 49). Nollet would later report successful attempts using porcelain vases. Note that van Musschenbroek here specifically mentions that he was researching glass in relation to the electric force. In the letter to Réaumur this is changed in the more general (and vague): "occupabar in detegendis Electricitatis viribus" ("Van Musschenbroek to Réaumur", *Procès-verbaux de l'Académie Royale des Sciences*, T65 (1746), p. 6, <https://gallica.bnf.fr/ark:/12148/bpt6k55741q>). A translation of the letter can be found in Heilbron, pp. 313–14 (note 1).

[84] According to the manuscript, the experiment was made on 17 December, 1745. Van Musschenbroek communicated this experiment in a letter to Réaumur, dated on 20 January 1746, which was mostly taken as the earliest written account of the experiment by van Musschenbroek (Heilbron, *Electricity*, p. 314 (note 1)).

[85] In the letter to Réaumur, the experiment is mentioned at the end of an account of meteorological observations. Rather than introducing the experiment as an important discovery, van Musschenbroek says that he will describe a new experiment that he had made as he saw "that this sheet has not yet been filled completely." ("van Musschenbroek to Réaumur", p. 6 (note 83))

[86] Although the manuscript provides valuable material which will have implications for our knowledge of the early history of the Leiden jar, and van Musschenbroek's understanding of this experiment, in what follows I will focus on the way the experiment described above should be understood in relation to the other experiments mentioned in the manuscript and van Musschenbroek's practice of experimentation. Further works needs to be done in order to arrive at a chronology of the added material (which seems to have been written and added at several occasions) and compare this with the existing narrative on the early history of the Leiden jar. It will also be necessary to look at the later editions of van Musschenbroek's textbooks, including the notes made in preparation to these new editions, which are also found among the manuscripts kept at Leiden University Library. All this lies beyond the scope of this article.

[87] In the following experiment, van Musschenbroek used two separate globes and iron rods, made the rods come together, let a man standing on resin touch the rods with his one hands and direct a spark to spirit of wine with his other. The spirit of wine started to burn (experiment 32, LUL BPL 240.18, fol. 74^{v} (note 49)).

[88] LUL BPL 240.18, fol. 74^{v} (note 49). Folium 71^{r} seems to contain an account of these variations (LUL BPL 240.18, fol. 71^{r} (note 49)). Here, van Musschenbroek mentions the use of German glass instead of Bohemian glass. In the letter to Réaumur he will say that "German or Bohemian glass" should be used (Heilbron, *Electricity*, p. 314 (note 1)). On folium 71^{r}, van Musschenbroek writes that he tried the experiment with a globe made from thin glass, and also with a small hexangular glass normally used for drinking jenever. In both cases the experiment succeeded. When he tried the experiment with a globe of English glass, all other things being equal, the experiment failed. In the experiment described on folium 71^{r}, van Musschenbroek says that he used a globe "[made] from thin, German glass with a diameter of about 5 inches" (LUL BPL 240.18, fol. 71^{r} (note 49)). In the letter to Réaumur, van Musschenbroek also describes the use of a globe of five inches in diameter (Heilbron, *Electricity*, p. 314 (note 1)). It is therefore probable that the folium contains the original account of the experiment later communicated to Réaumur. After Réaumur had read van Musschenbroek's letter to the *Académie*, he set out to replicate van Musschenbroek's experiment.

[89] Jean Antoine Nollet, "Observations Sur Quelques Nouveaux Phénomènes d'Électricité," *Mémoires de l'Académie Royale des Sciences*, 1746, pp. 5-6. He further mentions variations on the content of the jar. Any liquid will do the trick, except for greasy liquids such as oils and sulphurous liquids such as spirit of wine. The experiment also succeeded with mercury, iron filings and sand, but water still gave the best results (ibid., 6). Variations on the material of the vase led to the conclusion that only glass or porcelain can be used for this (ibid., 8). The manuscript of van Musschenbroek contains an added note in which he mentions Nollet's findings (including the fact that the type of glass is not the relevant finding) and describes a list of further exploratory experiments related to the surface of the glass (LUL BPL 240.18, fol. 72^{r} (note 49)). The verso side of the same folium contains proposals for further exploratory experiments related to the contents of the jar (LUL BPL 240.18, fol. 72^{v} (note 49)).

[90] Nollet, "Observations," p. 3 (note 89).

[91] LUL BPL 240.18, fol. 47^{r} (note 49), emphasis added.

[92] See the transcription and translation in Present, *Learning in the world*, pp. 249-85 (note 1).

[93] For example, on LUL BPL 240.18, fol. 79^{v} (note 49) van Musschenbroek writes that he was forced to abstain from performing experiments because of unfavorable weather conditions and added: "Other philosophers notified me that at the same time, in other parts and quarters of the city [i.e. Leiden], they performed experiments with the same lack of success so that electricity was absent from the air in all of the city."

[94] Van Musschenbroek, *Institutiones*, p. 202 (note 52).

[95] Van Musschenbroek, *Institutiones*, p. 203 (note 52).

[96] "The cause for the difference is that the [different kinds of] glass are not made from the same ingredients, nor are [these] mixed in the same proportion. Therefore [different kinds of] glass differ when it comes to their purity, transparency, weight, hardness, elasticity, solidity, etc. However, [different specimen] of glass which come from the same workshop and are made with the same crucible, are equally electric, as has been observed by Jallabert." (van Musschenbroek, *Introductio ad philosophiam naturalem* (Leiden: Sam. Et Joh. Luchtmans, 1762), p. 259) These remarks on glass are mentioned by Hackmann, who also discusses further developments in the research on the influence of the constitution of glass on the production of electricity (Hackmann, *Electricity from Glass*, 194-5 (note 21)).

[97] "Me trouvant justement dans ce tems à Leyde, chez Mssrs. MUSSCHENBROEK mes vénérables amis, nous n'avons pas manqué de mettre d'abord un globe de 12. pouces, verre d'Angleterre, en œuvre, avec lequel, après quelques tentatives, nous n'avons pas eu de peine d'allumer de l'esprit de vin." (Georg Matthias Bose, *Tentamina electrica* (Wittenberg: Apud Io. Ioach. Ahlfeldium, 1747), p. 28)

[98] "Il nous semble, que vôtre verre d'Allemagne vaut mieux pour ces expériences, que le verre d'Angleterre que nous emploions ici." (Bose, *Tentamina electrica*, p. 28 (note 97)).

[99] LUL BPL 240.18, fol. 74^{v} (note 49).

[100] LUL BPL 240.18, fol. 66^{r} (note 49).

[101] LUL BPL 240.18, fol. 53^{r} (note 49).

[102] LUL BPL 240.18, fol. 55^{r} (note 49).

[103] LUL BPL 240.18, fol. 61^{v} (note 49).

[104] For further discussion, see Present, *Learning in the world*, pp. 43-94 (note 1).

[105] Van Musschenbroek, *Institutiones*, p. 235 (note 52).

[106] Silva and Heering, "Re-examining the early history of the Leiden jar," p. 10 (note 1).

[107] Silva and Heering, "Re-examining the early history of the Leiden jar," p. 10 (note 1).

[108] LUL BPL 240.18, fols 71^{r}-73^{r} (note 49).

[109] Bose, *Tentamina electrica*, p. 37 (note 97).

[110] Heilbron, "G.M. Bose," p. 266 (note 4).

[111] Heilbron, "G.M. Bose," p. 266 (note 4).

[112] This concern with avoiding hasty generalizations reappears at many levels of van Musschenbroek's philosophical thought, for example in his views on laws of nature and his views on the role of mathematics in physics. For a discussion of van Musschenbroek's views on laws of nature, see Steffen Ducheyne and Pieter Present, "Pieter van Musschenbroek on Laws of Nature," *The British Journal for the History of Science* 50, no. 4

(2017): 637–656. For van Musschenbroek's views on the role of mathematics and their relation to the work of Bernard Nieuwentijt, see Steffen Ducheyne, "Constraining (Mathematical) Imagination by Experience: Nieuwentijt and van Musschenbroek on the Abuses of Mathematics," *Synthese* 196 (2019): 3595–3613. A general take on van Musschenbroek's methodological views can be found in Present, *Learning in the world*, pp. 43-94 (note 1) and Steffen Ducheyne, "Petrus van Musschenbroek and Newton's 'Vera Stabilisque Philosophandi Methodus'," *Berichte Zur Wissenschaftsgeschichte* 38, no. 4 (2015): 279–304.

[113] Van Musschenbroek, *Introductio*, p. 260 (note 96).

[114] Bose, *Tentamina electrica*, p. 45 (note 97).

[115] LUL BPL 240.18, fol. 61^{v} (note 49).

[116] LUL BPL 240.18, fol. 74^{r} (note 49).

[117] LUL BPL 240.18, fol. 74^{r} (note 49).

[118] LUL BPL 240.18, fol. 72^{v} (note 49).

[119] Bose, *Tentamina electrica*, pp. 45-6 (note 97).

[120] See for example: Geoffrey V. Sutton, *Science for a Polite Society: Gender, Culture, and the Demonstration of Enlightenment* (New York: Routledge, 2018); several contributions in Bernadette Bensaude-Vincent and Christine Blondel, eds., *Science and Spectacle in the European Enlightenment* (New York: Routledge, 2008); Mary Fairclough, *Literature, Electricity and Politics 1740–1840: 'Electrick Communication Every Where'* (London: Springer, 2017).

[121] Friedrich Steinle, "Entering New Fields," p. S65 (note 20). A further discussion of this "standard view" is given in Friedrich Steinle, "Experiments in History and Philosophy of Science" (note 20).

[122] See especially Heilbron, *Electricity*, p. 499 (note 1).

[123] Friedrich Steinle, "Concept Formation and the Limits of Justification: "Discovering" the Two Electricities" in Jutta Schickore and Friedrich Steinle (eds.), *Revisiting Discovery and Justification: Historical and Philosophical Perspectives on the Context Distinction* (Dordrecht: Springer Netherlands, 2006), pp. 183–95.