Galileo, measurement of the velocity of light, and the reaction times

Published version:

DOI:10.1068/p6263

(Article begins on next page)

Galileo, the measurement of the velocity of light, and the reaction times

Renato Foschi
Facoltà di Psicologia1, Università di Roma "La Sapienza", I-00185 Roma, Italy: e-mail: renato.foschi@uniroma1.it

Matteo Leone
Dipartimento di Fisica, Università di Genova, I-16146 Genova, Italy: e-mail: leone@fisica.unige.it

Abstract. According to the commonly accepted view, Galileo Galilei promoted in 1638 an experiment that seemed able to show that the speed of light is finite. An analysis of archival material shows that two decades later the members of Florence scientific society Accademia del Cimento followed Galileo guidelines by actually attempting measures of the speed of light and suggesting improvements. This analysis also reveals that a fundamental difference exists between Galileo's and Florence academy's methodologies and that Galileo's experiment was, in some respect, a pioneering work belonging also to the history of the psychology of perception.

1. Introduction

Galileo Galilei's writings contain some interesting observations on the nature and the reliability of senses within the context of the experimental work (Crombie 1972; Martinez 1974; Piccolino, Wade 2008). Of notable interest is a note on a *gedanken* procedure where the visual perception became the tool adopted by Galileo to check whether the velocity of light is a measurable quantity. However, while it is well known that modern physics ideas about the measure of the velocity of light originate in Galileo's work (see, for example, Ronzani, Maccarrone, Di Lieto 2008), the relevance of this procedure to the history of psychology needs to be properly assessed. This is the subject of the present paper.

In 1849, the French physicist H. L. Fizeau carried out the first successful laboratory measurement of the speed of light through the detection of a delay between incident and reflected rays against a plane mirror at a given distance when the light is made to cross a rotating cog-wheel. As it is discussed in the history of science literature (Mach 1898, Cohen 1940, Boyer 1941), the method developed by Fizeau (1849) closely followed one that was put forward by Galileo two centuries earlier. At the time of Galileo's method it was generally believed that the light travels at infinite speed. Among the most important supporters of the instantaneous propagation of light hypothesis figured Descartes who, in 1634, wrote to a friend, "for me this was so certain that if it could be proved false, I should be ready to confess that I know absolutely nothing about philosophy" (Cohen 1940, 334; Salmon 1977, 255). Although Galileo had previously advocated the view that light "may have an instantaneous motion" (Galilei 1623/1957, 278), by 1638 he was inclined to argue that the velocity of light is finite and, most importantly, suggested an experiment to set limits on its magnitude: if two observers (A and B), with lanterns, were at a considerable distance from each other, the time which observer A counted from the uncovering of his lantern until he caught sight of the light of B's would be the time which it would take the light to travel from A to B and from B back to A. As later emphasized by Ernst Mach, "the method devised by Galileo was as simple as it was natural" (Mach 1898, 57).

A close analysis of archival and printed material reveals however that, besides anticipating how to establish whether light had a finite velocity or not, Galileo's experiment was, in some respect, a pioneering work belonging also to the history of experimental psychology. According to the commonly accepted view, before around 1850 most scholars believed that human thought was instantaneous and that action was governed by an indivisible mind separated from the body (Boring 1950). Thus, "little or no effort was devoted before then to devising serious reaction-time procedures" (Meyer et al 1988, p. 6). While this conclusion is amply supported by the historiographical research findings, our analysis shows that Galileo grasped some elements of what was eventually named the experimenter "reaction time". If we compare Galileo's insightful approach with the one held thirty years later by the Florence academicians at the *Accademia del Cimento* who attempted to replicate and extend Galileo's findings, this conclusion is once more strengthened. By this analysis we discover indeed that although the experiments attempted – or just suggested – by the Florence academicians were conceptually similar to Galileo's one, and in one case still closer to the modern strategies to measure the speed of light, the delay due to the human experimenter got no further than the mere citing Galileo's words and was largely neglected when actually devising the experiments. Incidentally discovered by Galileo, this surprising effect did not survive his own "Galilean" followers.

2. Experiments

Galileo's experiment was originally discussed in his treatise on mechanics *Two New Sciences* (1638) (Galilei 1638/1974, OE page 43-44; ET page 50-51)[1]. After having reported about the experimental tools (two observers, each one with a lantern), Galileo hinted at the fact that the two observers introduce a delay factor, and devised a plan to reduce this factor:

> I would have two men each take one light, inside a dark lantern or other covering, which could conceal and reveal by interposing his hand, directing this toward the vision of the other. Facing each other at a distance of a few braccia[2], they could practice revealing and concealing the light from each other's view, so that when either man saw a light from the other, he would at once uncover his own. (Galilei 1638/1974, OE page 43; ET page 50).

By means of this "practice", Galileo emphasized soon afterwards, it was possible to "adjust" this signaling:

> After some mutual exchanges, this signaling would become so adjusted that without any sensible variation, either would immediately reply to the other's signal, so that when one man uncovered his light he would instantly see the other man's light. (Ibid, OE page 43; ET page 50)

According to Galileo's methodology,

> this practice having been perfected at short distance, the same two companions could place themselves with similar lights at a distance of two or three miles and resume the experiment at night, observing carefully whether the replies to their showings and hidings followed in the same manner as near at hand. If so, they could surely conclude that the expansion of light is instantaneous, for if light required any time at a distance of three miles, which amounts to six miles for the going of one light and the coming of the other, the interval ought to be quite noticeable" (Galilei 1638/1974; OE page 43-44, ET page 50).

Galileo reported having actually attempted the experiment at less than a mile. The choice of the distance between the lanterns was supported by Galileo's observation that, when a thunderstorm happens, "the lightning seen between clouds eight to ten miles away […] takes some little time" (Galilei 1638/1974, OE page 44; ET page 51). Therefore, Galileo apparently reasoned, if we are able to "distinguish the […] very wide expansion [of the light] through surrounding clouds", then experiments at similar lengths might yield positive results unless the "illumination were made all together and

[1] When quoting from Galileo's *Two New Sciences* we indicate the page numbers of the original Italian edition (Galileo 1638) followed by the notation ET with the page numbers of the English translation.

[2] The Florentine "braccio", used by Galileo, was about 60 cm long, as can be seen in the reference bars fixed on the external walls of the town hall in Pistoia; see Straulino 2008.

not by parts". Yet, as it is well known, he was not able "to make sure whether the facing light appeared instantaneously" (Galilei 1638/1974, OE page 44; ET page 50).

Decades later, the experiment on the velocity of light was also unsuccessfully performed by the scientific *Accademia del Cimento* of Florence (1657-1667). This academy, founded by the Medici princes, Ferdinando II, Grand Duke of Tuscany, and his brother, Leopoldo, later Cardinal, was the earliest scientific society devoted exclusively to experimentation, according to Galileo's agenda (Middleton 1971; Beretta 2000). The first secretary of the academy was Alessandro Segni, who was initiated into geometry by Evangelista Torricelli. By May 20, 1660, Lorenzo Magalotti had replaced Segni, and a few years later he wrote the only publication of the academy, the *Saggi di naturali esperienze fatte nell'Accademia del Cimento*, which was published anonymously in 1667 under his title as secretary. The *Saggi* was delayed for at least five years after the material for it was available, and even before the publication of this work the Accademia del Cimento had ceased to exist (Middleton 1980).

> The trial consists in the confederacy of two companies of men to expose two lights to each other view, so that the discovery of the one, may answer immediately to that of the other […]. This being often practiced at a small distance, Galileo desired to have the same tried by observers at a greater distance, to see if the mutual correspondence of exposing and covering their lights, kept the same measure as when nearer, that is without any observable delay.
> We tried it at a miles distance […] and could not observe any [delay]. If in a greater distance it be possible to perceive any sensible delay, we have not yet had an opportunity to try (Magalotti 1667/1684, OE page 265-266; ET page 157; the translation has been slightly modified).

The account published in the *Saggi* is quite similar to the one discussed by Galileo in *Two New Sciences*, the only difference being the distances involved (less than a mile, according to Galileo; a mile according to the Accademia del Cimento report). These two accounts suggest, therefore, that the Florence academicians planned, and allegedly attempted, an experiment strictly according to Galileo's guidelines. In order to get further details on this experiment, we have carried an analysis of the relevant Florence academy diaries, notes and letters housed in the Biblioteca Centrale Nazionale in Florence (BCNF). Unexpectedly, our work indicates that the match between Galileo's and Accademia del Cimento's methodologies is less than expected.

3. Archival sources

A close analysis of the archival material reveals that the Florence academicians frequently addressed the issue of whether the velocity of light is finite or not. Moreover, in a number of unpublished letters and reports, possible improvements of Galileo's methodology were tentatively outlined. One of these improvements was reported in an undated note written by Vincenzo Viviani, who had been Galileo's secretary during the last years of his life, and who had, by October 1656, measured the velocity of sound by timing the difference between the flash and the sound of a mortar fired near Florence (Boschiero 2005, 87). According to Viviani, the question of whether or not light had finite velocity might be settled by experimenting at distances larger than one mile.

> In order to see if the motion of light is instantaneous or takes time, light a large fire on the dome [in Florence] and a similar one on the Verrucola[3]. At night, keep the fire alight for a long time, then cover the fire on the dome and look at the Verrucola to see if the other fire, uncovered by the friend right after he sees yours, is visible. (Viviani no date).

Another unknown academician (but, according to the 1780 edition of *Saggi*, he likely was Carlo Rinaldini, one of the only two members of the academy who had

[3] Mount Verruca near Pisa.

sympathy for the Aristotelian thought) (Targioni Tozzetti 1780) suggested a number of ways to establish "if light is instantaneous, or if it moves in time". According to the first method suggested by the academician, one observer

[…] lights a fire on Verucola, in a way that it is possible to cover and uncover it at pleasure, and that the uncovering is as quick as possible. Then, [another observer] rests observing either on the top of Pisa bell-tower or in another elevated place […]. When the observer on Verucola sees the end of moonset, he uncovers his own fire. Thus, when the other observer sees the same end of moonset, if he does not see the uncovered fire of Verucola [at the same time], then this will be an evident clue that the expansion of light has required time. The time will be as much as the pendulum [*bindolo*] vibrations counted from the end of moonset to the appearance of the light (Rinaldini no date).

The same academician suggested to set-up two more experiments, where three experimenters were involved. According to the first suggestion, a fire is uncovered at half the distance between Pisa and the Verruca mountain[4]. When an observer on the mountain sees the light he uncovers his own fire, and a second observer in Pisa looks at the possible delay. Or, in alternative, a cracker is let off at half the distance as above, and when the observer on the mountain hears the sound, he lights a fire and allows a second observer in Pisa to check for a possible delay between sound and light.

Two academicians, Viviani and Magalotti, actually arranged and carried out some preliminary, and inconclusive, fire lighting experiences between Florence and Pisa, as they reported in a set of notes titled "Report on the fires lighted on the top of the bell-tower of the S.M. del Fiore church in Florence on July 24, 1663". The experiences were aimed at discovering

[…] the suitable kind and size of a fire lighted at night in order to distinguish it at a 20 miles distance, i.e. from Florence to Pisa, […] with the goal of carrying out the experiment on the motion of light and establishing if this motion is instantaneous or if it requires time. (Magalotti &Viviani no date)

The mentioned suggestions did not exhaust the wealth of possibilities taken into account by Florence academicians. As reported by Giovanni Alfonso Borelli, who at the Accademia del Cimento began his long standing interest into the science of animal movement, it might be possible to detect a delay due to the multiple reflections of the light against a system of plane mirrors (according to the arrangement of Figure 1), thereby anticipating Fizeau's experiment. In his April 14, 1657 letter to Leopoldo de' Medici (Borelli 1657; Fabroni 1775; Giovannozzi 1926-1927*)*, he wrote as follows:

the ray of light starts from A toward the mirror BC. Then, it has to follow the paths AD, DG, GM, MP, PS, SA before going back in A. As it is known the exact time when the light is uncovered […], if it is true that the expansion of light requires time, then the interval ought to be noticeable. But, if the light starts from A toward D so that the light from S reaches at the same time the viewpoint A, then we could surely conclude that the light does not require time. […] If I am not mistaken, this is the most exquisite experience one might imagine in this connection. Thus, I hope to be able to carry out it next summer, with the help and support of Your Serene Highness (Borelli 1657, 65).

While it is unclear whether Borelli actually carried out his experience, his plan was an indisputable improvement over Galileo's one since it replaced one human experimenter by a set of mirrors. A simpler version of Borelli's experience was previously, and independently, put forward by Dutch physicist Isaac Beeckman, as outlined by a private letter from Descartes to Beeckman, dated August 22, 1634; according to Beeckman, an observer would move a lantern in front of a mirror placed at a quarter of a mile and the interval between moving the lantern and perceiving its

[4] The distance between the leaning tower of Pisa and Mount Verruca is about 7 miles.

reflection in the mirror would offer a measure of the speed of light (Cohen 1940; Shea 1978).

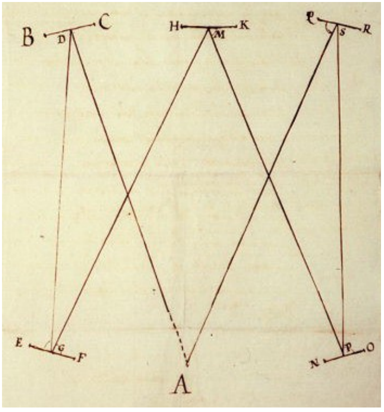

Fig. 1. Borelli's planned experiment for establishing whether speed of light is finite through a set of plane mirrors. (Reproduced from http://193.206.206.9/cgi-galileo/viewimg.pl?nfolio=275&unita=39.).

To summarize: before 1638, Galileo planned an experiment to establish whether the speed of light is finite or not. As he reported in *Two New Sciences*, he allegedly carried out some experiments, but to no avail. The project was kept up two decades later by his followers of Accademia del Cimento. According to their published report, their experience was unsuccessful as well. However, by cross-checking as above the details reported in *Two New Sciences* and *Saggi* with the original data extracted from the relevant Galilean manuscripts, a radical difference between the approaches followed by Galileo and the Florence academicians emerges. As it will be discussed in the following section, this difference consists in the actual discovery of a psycho-physical quantity – the "reaction time" – by Galileo. A discovery that, as we have shown, plays no role in Florence academicians planned experiments.

4. Reaction times

The contents of the relevant paragraphs of *Two New Sciences* and *Saggi* show that Galileo was aware of the fact that by experimenting with two experimenters a delay factor was introduced. We know about this by his realizing that it was possible to reduce this delay by an adequate "practice" allowing the signaling between the experimenters to become "adjusted" (Galilei 1638/1974, OE page 43; ET page 50). Furthermore, "this signaling would become so adjusted that *without any sensible variation*, either would *immediately reply* to the other's signal, so that when one man uncovered his light he would *instantly* see the other man's light [emphasis added]" (Ibid, 50). Upon reaching this practice threshold, Galileo wrote, the speed of light might be easily estimated by measuring whether "showings and hidings" did occur "in the same manner" at short as well as at long distances (Ibid, 50).

These latest remarks might be interpreted as indicating that Galileo had understood that repeated trials brought the time lapse to a constant threshold greater than zero, and that, by a differential method, the speed of light estimate is independent of a constant experimenter's delay factor (in modern language, if we let s_1 = short distance, s_2 = long distance, t_{R1} = delay factor at short distance, t_{R2} = delay factor at long distance, and v = velocity of light, we obtain for the time intervals t_1 and t_2: $t_1 = 2\left({s_1}/{v} \right) + t_{R1}$; $t_2 = 2\left({s_2}/{v} \right) + t_{R2}$; hence, if $t_{R1} = t_{R2}$, one obtains $v = 2\frac{s_2 - s_1}{t_2 - t_1}$).

This interpretation of Galileo's words, i.e. the view that repeated trials shortened the time lapse to a finite quantity as opposed to zero would be strengthened by an alternative translation of the original Italian text.[5] Since the Renaissance Italian term "tenore" had also a musical meaning, we might be led to translate Galileo's expression "l'istesso tenore" as "with the same pace" rather than with the standard phrase "in the same manner" (Galilei 1638/1974, OE page 44, ET page 50; see also the translation by H. Crew and A. De Salvio, New York, 1914, page 88). If this alternative is adopted, Galileo's experiment would become one of assessing whether the rhythm of the occlusions and discoveries of the lantern slow down when the trained observers are at a greater distance. Did Galileo plan to count the cycles of the observers over a longer period while also counting the beats of a pendulum? Although interesting and provocative, this interpretation appears unlikely for a number of reasons.

First, in Seventeenth Century Italy the word "tenore" had many meanings, the main one being "forma, maniera" (form, manner): see, for example, *Dizionario degli Accademici della Crusca* (Venezia: Giovanni Alberti, 1612). This meaning was well known to Galileo as it is shown by the numerous instances where he used the "l'istesso tenore" expression to convey a sense of "same manner", devoid of musical underpinnings, e.g. when discussing the relativity of motions (Galilei 1632/1967, OE page 172), the velocity of falling bodies (Galilei 1638/1974, OE page 257), the magnification power of the telescope (Galilei 1623/1957, OE page 86), and the effect of the change of scale on the laws of physics (Galilei 1638/1974, OE page 124). A further reason against this interpretation of Galileo's experiment may be obtained by reading "l'istesso tenore" expression within the context of Galileo's account. Nowhere in the relevant paragraphs in Galileo is there any implication of uninterrupted cycles of occlusions and discoveries whose *total time* had to be measured via a pendulum. On the contrary, "l'istesso tenore" phrase follows a sentence where Galileo explains that after the adjustment between the experimenters, "either would immediately reply to the other's signal, so that when one man uncovered his light he would instantly see the other man's light" (Galilei 1638/1974, OE page 43; ET page 50): here, Galileo is straightforward and unequivocal in suggesting that practice would cancel the human time lapse. Other interpretations would conflict with the actual contents of Galileo's report. Finally, this is just the way the contemporaries of Galileo, namely the Florence academicians, interpreted their Master's work. In the *Saggi di Naturali Esperienze* relevant passage, after reporting Galileo's words "secondo l'istesso tenore che facevano da vicino", the Florence academicians added the specification "*cioè senza dimora osservabile*", i.e. "without any observable delay" (Magalotti 1667/1684, OE page 265; for "dimora" as "indugio, tardanza", i.e. "delay" see also *Dizionario degli Accademici*, cit.). Again, no reference was made to the delay in transmission who would become apparent if an uninterrupted cycle of occlusions and discoveries was conducted.

In retrospect, therefore, Galileo had observed 1) the existence of a delay when two human experimenters were involved, and 2) the effect of practice upon this delay (as we have shown above, he was unequivocally favorable to the view that practice reduces the delay to zero). Next, he devised what was to become a couple of "simple reaction time" experiments, i.e. estimates of the intervals between the onset of a stimulus and the motor response to it, at different distances. As it is well known, the reaction times methodology, i.e. the first quantitative foundations of the emerging experimental psychology, was developed in nineteenth century, after a number of developments, namely F.W. Bessel's discovery of the "personal equation" affecting astronomer's transit time measurements, H. von Helmholtz's measures of the "finite" velocity of

[5] We are grateful to an anonymous referee for offering us this alternative reading of Galileo's words.

nervous impulse[6], F.C. Donders estimates of the "duration of simple mental processes", S. Exner's estimates as a "reaction time" of the velocity of the nervous impulse, and the invention of the chronoscopes for the psychological experiments (Mollon & Perkins 1996; Robinson 2001; Schmidgen 2003, 2005). By the end of nineteenth century it was generally acknowledged that among the factors affecting the average value of the reaction time was the amount of practice. As reported by Titchener (1905, 359): "the time of reaction, like all other psychophysical 'constants', varies with the conditions under which it is determined; an accurate result presupposes [...] maximal practice. [...] Wundt has recently laid great stress upon *the necessity of maximal practice* for the final determination of representative values and of their variability" [emphasis added].

Galileo had grasped that the reaction times are much more consistent after adequate preliminary training. However, differently of the modern view, he believed that the repeated trials consistently reduced the time lapse to zero. This conclusion was hardly surprising since the average 0.2 s reaction time to light (Titchener 1905) was below the 0.5 s sensitivity of the available pendulum chronometers (Magalotti 1667/1684).

All of the above refers to Galileo's account only. As regards the experiments planned by the Accademia del Cimento members, the analysis of the archival material led to rather different an outcome. Apart from Borelli's project, where the delay issue was avoided as the second observer was replaced by a set of mirrors, the reaction times phenomenon failed indeed to capture the interest of the Florentine academicians. The whole set of fire lighting experiences between Florence, Pisa and Mount Verruca, proposed by Rinaldini and Viviani, assumed, without any discussion, that the time lapse between visual stimulus and motor response is nil. As Rinaldini wrote, concerning the planned three-experimenters experiences, "it is assumed, however, that the uncovering of one fire and the uncovering of the other one happen at the same time or at insensibly different times" (Rinaldini no date).

As we have discussed, the preliminary practice was an integral part of Galilean methodology. Only if this preliminary training was performed the experimenters "could surely conclude" that the expansion of light is instantaneous or not (Galilei 1938/1974, OE page 44; ET page 50). Yet, in the academy notes and reports, no mention is ever made of the effects that this practice had upon the measurements.

5. Conclusions

Galileo is known for having introduced a rigid distinction between our sensations of the objects (e.g. color, smell, taste) and the properties residing in external objects (Galilei 1623/1957, 274; cf. Crombie 1972; Martinez 1974; Piccolino, Wade 2008), i.e. Locke's distinction between secondary and primary qualities, as discussed in his *Essay on the Human Understanding*. With the goal of measuring a primary quality – the velocity of light – he planned an experiment where a secondary quality was discovered – the human reaction time to light. In order to get rid of this unwanted time lapse, Galileo devised a training methodology where the experimenters had to synchronize each other. By repeated trials the experimenters were allegedly able to cancel the time lapse, i.e. an outcome which confirmed to Galileo that no primary quality was involved (primary qualities are immune to repeated trials; e.g. when experimenting on the law of fall, Galileo had observed that no departure from the law had exceeded one-tenth of a pulsebeat after a hundred trials; see Drake 1986).

[6] Helmholtz's experiments are particularly relevant in this context because he was in a condition somewhat similar to that of Galileo with the light measuring a fast phenomenon with a relatively slow detection system (in Helmholtz's case muscle contraction) (Cahan 1994; Debru 2001; Finger, Wade 2002).

The analysis of the archival material has shown that this practice, which was eventually at the core of the late nineteenth century experiments on reaction times, was neglected by the Florence academicians following Galilean scientific agenda. One of the reasons for this neglecting is likely the expected low magnitude of the velocity of light, an expectation which was rooted in the apparently sensible motion of lightning between clouds. Although Galileo's interpretation of this observation was wrong – the velocity of electric discharges such as lightning is significantly lower than the actual speed of light (Brantley et al 1975) – many other reliable observers eventually reported discerning direction of movement and propagation in long-duration lightning flashes (D'Abbadie 1887; Brook & Vonnegut 1960; Krider 1974); this phenomenon has been interpreted either as a pure perceptual effect (Bozzi 1995) analogue to the "gamma movement" (Kenkel 1913) or as an effect due to the close proximity between the measured velocities for lightning flashes and the upper threshold for detection of movement by the human eye (Baker & Baker-Blocker 1986).

Of course, if it was expected that the velocity of light was of the order of a few miles per second (Galilei 1638/1974, OE page 44; ET page 51), experiences at greater distances than those planned by Galileo might yield positive results independently of any human time lapse. For example, if the distance in the planned Accademia del Cimento experiences between Mount Verruca and Pisa was not felt to be large enough, "the experience might be carried out at a much greater distance, where it would be likely that if the motion of light requires time, its duration would be discovered" (Rinaldini no date). In some respect, a wrong expectation about the velocity of light magnitude did not favour the emergence of empirical studies on reaction times in Seventeenth-Century Italy.

Acknowledgments. The authors are listed in alphabetical order as they contributed equally to this article. They gathered the data and discussed the results together. The authors also express their gratitude to Vilfredo De Pascalis, Giuseppe Giuliani, Patrizia Guarnieri, Horst Gundlach, Giovanni Pietro Lombardo and Nadia Robotti for critically reading previous versions of the manuscript.

References

Baker D G, Baker-Blocker A, 1986 "Visual observation of lightning propagation" *Nature* **322** 215

Beretta M, 2000 "At the source of western science: the organization of experimentalism at the Accademia del Cimento (1657-1667)" *Notes and Records of the Royal Society of London* **54** 131 - 151

Borelli A, 1657 *Letter to Leopoldo de' Medici* (April 14th), Galilean manuscripts, Posteriori T.16, Fondo Palatino 275, Folio 65 BCNF

Boring E G, 1950 *A history of experimental psychology* (New York: Appleton-Century-Crofts)

Boschiero L, 2005 "Post-Galilean thought and experiment in seventeenth-century Italy: the life and work of Vincenzo Viviani" *History of Science* **43** 77 - 100

Boyer C B, 1941 "Early Estimates of the Velocity of Light" *Isis* **33** 24 - 40

Bozzi P, 1995 "Osservazione e percezione. (Velocità della luce ed effetto γ)" in *Galileo e la scienza sperimentale* Ed M. Baldo Ceolin (Padua: Dipartimento di Fisica "Galileo Galilei") pp. 112-118

Brantley R D, Tiller J A, Uman M A, 1975 "Lightning properties in Florida thunderstorms from video tape recordes" *Journal of Geophysical Research* **80** 3402 - 3406

Brook M, Vonnegut B, 1960 "Visual confirmation of the junction process in lightning discharge" *Journal of Geophysical Research* **65** 1302 - 1303

Cahan D, 1994 *Hermann Von Helmholtz and the Foundations of Nineteenth-century Science* (Berkeley: University of California Press)

Cohen I B, 1940 "Roemer and the First Determination of the Velocity of Light" *Isis* **31** 327 – 379

Crombie A C, 1972 "The primary properties and secondary qualities in Galileo Galilei' natural philosophy" in *Saggi su Galileo Galilei* Ed C Maccagni (Firenze: Barbera) pp 71 – 91

Debru C, 2001 "Helmholtz and the Psychophysiology of Time" *Science in context* **14** 471 – 492

D'Abbadie A, 1887 "Lightning-Flashes" *Nature* **35** 342

Drake S, 1986 "Galileo's physical measurements" *American Journal of Physics* **54** 302 – 306

Fabroni A, Ed, 1775 *Lettere inedite di uomini illustri*, Tomo 2 (Firenze: Moücke)
Finger S, Wade N, 2002 "The neuroscience of Helmholtz and the theories of Johannes Müller: Part 1: Nerve Cell Structure, Vitalism, and the Nerve Impulse" *Journal of the History of the Neurosciences* **11** 136 – 155
Fizeau H L, 1849 "Sur une experience relative a la vitesse de. propagation de la lumiere" *Comptes Rendus de l'Académie des Sciences, Paris* **29** 90 - 92
Galilei G, 1623 *Il Saggiatore, nel quale con bilancia esquisita e giusta*... (Rome: Mascardi). English translation by S Drake in *Discoveries and opinions of Galileo* (New York: Doubleday & Co., 1957)
Galilei G, 1632 *Dialogo sopra i due massimi sistemi del mondo tolemaico e copernicano* (Florence: Landini). English translation by S Drake in *Dialogue concerning the two chief world systems, Ptolemaic and Copernican* 2nd edition, 1967 (Berkeley, CA: University of California Press)
Galilei G, 1638 *Discorsi e dimostrazioni matematiche, intorno a due nuove scienze* … (Leiden: appresso gli Elsevirii). English translation by S Drake in *Two New Sciences* (Madison, WI: University of Wisconsin Press, 1974)
Giovannozzi G, 1926-1927 "Una lettera di Francesco Famiano Nichelini a Giovanni Alfonso Borelli *Atti della Pontificia Accademia delle Scienze* 80, 315-319
Kenkel F, 1913 "Untersuchungen über der Zusammenhang zwischen Erscheinungsgröße und Erscheinungsbewegung bei einigen sogenannten optischen Täuschungen" *Zeitschrift für Psychologie,* **67** 358 - 449
Krider E P, 1974 "An unusual photograph of an air lightning discharge" *Weather* **29** 24 - 27
Mach E, 1898/1986 *Popular scientific lectures* (La Salle, IL: Open Court, 1986)
Magalotti L, 1667/1684 Saggi di Naturali Esperienze fatte nell'Accademia del Cimento (Florence: Cocchini). English translation by R Waller in *Essayes of Natural Experiments made in the Academie del Cimento* (London: Benjamin Alsop)
Magalotti L, Viviani L, no date *Galilean manuscripts*, Posteriori T.9 Cimento. Fisica Sperimentale vol. 9 Memorie e spoglio di esperienze. Fondo Palatino 268, Folio 167r-172r BCNF
Martinez J A, 1974 "Galileo on Primary and Secondary Qualities" *Journal of the History of Behavioral Sciences* **10** 160 - 169
Meyer D E, Osman A M, Irwin D E, Yantis S, 1988 "Modern mental chronometry" *Biological Psychology* **26** 3 - 67
Middleton W E K, 1971 *The experimenters: a study of the Accademia del Cimento* (Baltimore/London: Johns Hopkins Press)
Middleton W E K, Ed, 1980 *Lorenzo Magalotti at the Court of Charles II* (Waterloo, Canada: Wilfrid Laurier University Press)
Mollon J D, Perkins A J, 1996 "Errors of judgment at Greenwich in 1796" *Nature* **380** 101 – 102
Piccolino M, Wade N, 2008 "Galileo's eye: A new vision of the senses in the work of Galileo Galilei" *Perception* **37** 1312 – 1340
Rinaldini C, no date *Galilean manuscripts*, Posteriori T.9 Cimento. Fisica Sperimentale vol. 9 Memorie e spoglio di esperienze. Fondo Palatino 268, Folio 166r BCNF
Robinson D K, 2001 "Reaction-time experiments in Wundt's Institute and beyond" in *Wilhelm Wundt in history: The making of a scientific psychology* Eds R W Rieber, D. K. Robinson (New York: Kluwer Academic/Plenum Press) pp 161 – 204
Ronzani A, Maccarrone F, Di Lieto A, 2008 "Measuring light speed with a modulated laser diode" *European Journal of Physics* **29** 957 – 965
Salmon W, 1977 "The philosophical significance of the one-way speed of light" *Noûs* **11** 253 - 292
Schmidgen H, 2003 "Time and noise: the stable surroundings of reaction experiments, 1860 – 1890" *Studies in History and Philosophy of Biological and Biomedical Sciences* **34** 237 - 275
Schmidgen H, 2005 "Physics, ballistics, and psychology: a history of the chronoscope in/as context, 1845-1890" *History of Psychology* **8** 46 - 78
Shea W R, 1978 "Descartes as critic of Galileo", in *New Perspectives on Galileo* Eds R W Butts, J C Pitt (Dordrecht: D. Reidel) pp 139 – 159
Straulino S, 2008 "Reconstruction of Galileo Galilei's experiment: the inclined plane" *Physics Education* **43** 316 - 321
Targioni Tozzetti G, Ed, 1780 *Atti e Memorie Inedite dell'Accademia del Cimento* (Firenze: Tofani)
Titchener E B, 1905, *Experimental Psychology. A Manual of Experimental Practice. Volume II Quantitative Experiments. Part II. Instructor's Manual* (New York: Macmillan)
Viviani V, no date *Galilean manuscripts*, Posteriori T.10 Cimento. Fisica Sperimentale vol. 10 Miscellanee I. Fondo Palatino 268, Folio 60r BCNF