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Introduction

The aim of this work is to make a two-fold contribution to the study of eighteenth-century science. The majority of this book is devoted to a description and analysis of the conceptual development of physical optics in the period, focussing on the origins, contents, and reception of Leonhard Euler's wave theory of light. There will always be a second question in the background of the narrative, which will receive full attention in the last chapter: What does a study of eighteenth-century optics have to teach us about the changing nature of natural philosophy and science in that period?

The title of this study – *Optics in the Age of Euler* – constitutes a response to the still generally accepted historical image of optics in which the eighteenth century is portrayed as the century of Newton.[1] According to the standard account, 'Newton's' particle, or emission, theory of light dominated for more than a century, whereas 'Huygens'' wave, or medium, theory supposedly did not develop and found few supporters during the same period. This study provides a corrective to this image, with the Swiss mathematician and natural philosopher Leonhard Euler (1707–83) a leading figure in the new historiographical drama. Euler's importance derives from his "Nova theoria lucis et colorum" (A new theory of light and colours), published in 1746. This article was the foremost eighteenth-century contribution to the development of the medium theories of light. Euler's theory of light, rather than Huygens' theory, was the first serious rival to the emission theories. The present study reveals that Euler's influence was particularly strong in the German lands. Indeed, during the period 1755–90 in Germany the champions of Euler's theory were in the majority.

The title *Optics in the Age of Euler* should not be taken to imply that Euler, rather than Newton, dominated eighteenth-century optics. This is definitely not my intention. However, focussing on Euler and the reception of his theory in Germany allows us to draw a more complete and somewhat different picture.[2] In particular, three themes come to the fore in the present perspective. First, the development of the medium theories of light from Huygens to Euler has been given little treatment in the literature so far. It turns out to be a far more complex and interesting story than has been realized, for example, concerning the different ways in which the concept of periodicity was introduced. Second, studying Euler draws our attention to the slow emergence of the debate between two, and not more than two, optical traditions, the medium tradition and the emission tradition, in the decades before 1746. Contrary to what has been generally assumed, in an important sense the 'wave–particle debate' only starts with Euler. Third, the study of the reception of Euler's theory of light in Germany reveals in a striking way the relevance of chemistry to the assessments of optical theories in the eighteenth century.

In this introductory chapter we shall first examine in greater detail the standard image of eighteenth-century optics and the assumptions underlying it. Next I shall define a number of the main terms used in the text, and finally there is an outline of the way this study is constructed.

1. Condensation and presentism in the historiography of optics

The history of science is sometimes regarded as a triumphal procession of 'great men':[3] The genius, such as Galileo or Newton, produces the insights that determine the course of scientific development. This version of history often leads to 'historical condensation'. Just as the heroic deeds of various people are compressed into the actions of one central figure in the tales of King Arthur, so Newton, the great luminary of the Enlightenment, is superbly suited to the role of legendary hero in the history of science. Consequently, some ideas have been attributed to him, although at best he held them only in an incomplete way or in another form. In many cases natural philosophers coming after him worked out his ideas and suggestions, enriched them with their own discoveries or arranged them in a systematic way. Where their role was forgotten, the image of Newton expanded into an overpowering centre of attraction, rendering the other figures anonymous and encorporating their contributions.

For example, by means of this process the present-day meaning of the second law of mechanics, usually represented by **F** = ma, came – in all its glory – to be attributed to Newton. Yet many other scientists, among whom Euler occupies a prominent position, contributed to the history of this law.[4] Newton's role in the history of optics also provides us with a splendid example of historical condensation. We are concerned here with the authorship of 'the' eighteenth-century emission theory of light, which states that light sources emit matter, for example, a stream of immensely tiny particles that produce a visual perception in our eyes. Many writers regarded Newton as the author of this theory, adding in the same breath that the eighteenth century had on the whole accepted the emission theory of light, mainly because of Newton's great authority.[5] This statement not only contains an invalid generalisation embodied in the expression 'on the whole'; it also contains an inadmissable simplification of the actual course of events. Eighteenth-century natural philosophers were in no position to accept Newton's emission *theory*, even had they wanted to do so. Newton's heritage consisted of a number of different, even incompatible, suggestions throughout the *Opticks* and especially in the Queries. The task completed by his contemporaries and successors was not an easy one, and positively demanded a personal contribution from each. Taking Newton's suggestions as their starting point, they constructed a theory demonstrating greater coherence and consistency than the original comments. This 'Newtonian' programme was first completed in the 1720s and 1730s, and it is only from this period that one can talk of the acceptance or rejection of an emission *theory*. Moreover, the 'Newtonian' emission theory *in statu nascendi* was not the only emission hypothesis in the early eighteenth century. There were other embryonic emission theories that bore no relation, or a less exclusive relation, to Newton's suggestions.

According to the received account, Christiaan Huygens was Newton's great rival. He has also suffered historical condensation, for is he not regarded as the foremost advocate of 'the' wave theory of light? However, he cannot be counted as a wave theorist and the main rival of Newton for three significant reasons. First, he explicitly rejected a basic element of a wave theory of light, that is, the periodicity of the pulses.[6] Second, he acknowledged that he had omitted the explanation of colours because the task was too heavy for him. This major omission alone would have been enough to eliminate Huygens' theory as a serious rival to an emission theory. The third reason concerns Huygens' explanation for the rectilinear propagation of light. As will be shown in Chapter 3, this explanation was generally considered inadequate. The alleged failure was cited as the main argument for rejecting Huygens' theory, but Huygens' explanation was also criticized by those who supported a different kind of medium theory.[7] More than half a century after Huygens, Euler produced a medium theory of light that also accounted for a range of colour phenomena. The concept of frequency and the associated periodicity of pulses occupied a central position in Euler's theory. Consequently, only with Euler do we have what we usually call a *wave* theory of light. By contrast, Huygens' conception is best indicated as a *pulse* theory. Although Euler's explanation of rectilinear propagation of light was unable to convince everyone, his theory was considered a serious competitor to the emission theories. (To avoid creating a new legendary figure, it should be mentioned that Euler was indebted to previous optical theorists – among whom Huygens, surprisingly enough, occupies a modest position.)

A peculiarity of many earlier historical studies is that their norms of evaluation were derived from contemporary knowledge. For example, Aristotle's physics or Ptolemy's geocentric world system were not considered from the context of their own times, but were assessed on the basis of a comparison with the current state of physics and astronomy, which often amounted to condemnation or – its complement – praise of insights 'already' possessed in an earlier age. The current day could thus influence the view of the past in this fairly direct manner.

It could also work in a more subtle way: Evaluation was based not on the current state of knowledge, but on the current manner in which science defined its problems. Again, we find an example of this in the historiography of optics. In the 1920s a vital choice to be made in optics lay at the centre of scientific interest: Did light consist of a stream of emitted 'particles' (light quanta), or was it a wave motion? A parallel was drawn with the celebrated debate at the beginning of the nineteenth century, when an emission theory based upon Newton's suggestions and developed further especially in France competed with Fresnel's wave theory for the favours of the scientific community. It was only natural to see the late seventeenth and early eighteenth centuries in the same dualistic terms. Had Newton not defended 'the' emission theory, and Huygens 'the' wave theory? There was a strong temptation to answer in the affirmative here, for what could be more dramatic than a continuous reincarnation of thesis and antithesis, certainly for someone witnessing the synthesis of the contradictions in quantum mechanics?[8]

The dualistic view of the history of optics and the historical condensation where Newton and Huygens are concerned afforded mutual reinforcement. In their close cooperation they created a distorted image of optics at the end of the seventeenth century. According to this picture, the debate between the emission and the wave theories was the central problem at that time, but that view is incorrect, if only because neither theory existed in that period. More important, the optics of the late seventeenth century, as well as that of the early eighteenth century, was dominated by an entirely different issue: the nature of colours. In 1672 Newton had put forward new ideas on this subject, thereby attacking a centuries-old tradition and consequently earning a great deal of criticism from his contemporaries. Admittedly, in the exchanges about colours the opposition between emission and medium conceptions also arose, but the issue had no dominant role and certainly not the elaborately costumed part in which we encounter it seventy-five years later, in the mid-eighteenth century. At that time both emission and wave theories were finally present in a systematically organised form. The ensuing debate did indeed revolve around the question of whether the propagation of light was an emission of matter or a motion in an ethereal medium. However, for the two reasons given here, standard historiography has not recognised the slow emergence of the wave–particle debate in optics in the period between Newton and Euler, and it has missed the significance of the actual wave–particle debate in the second half of the eighteenth century. Ironically, what historians of science on the basis of doubtful premises thought they could find in the seventeenth century, has in fact taken place in the eighteenth century.

2. Terminology and outline of this book

Some of the problems arising from the old historical image of optics are interwoven with the language used. One example of this can be seen in the way some authors talk of 'the' wave theory, making no distinction between Huygens' theory, which was a pulse theory, and later theories of light that could more justifiably be called wave theories. Another example is provided by the identification of Newton's suggestions for an emission theory of light with the systematized emission theories of the mid-eighteenth century. To prevent the elaboration of a new image from being handicapped by these mistaken associations, the key terms used in the following chapters will be discussed.

The first set of terms classifies the various kinds of hypotheses about

Table 1. *Conceptions of the nature of light in Classical Antiquity*

	Effect from the object to the eye	Effect from the eye to the object
Active medium	Propagation of the effect by the medium (Aristotle)	Eye rays with medium (Stoics)
No active medium	Emission of matter (atomists)	Eye rays without medium (Euclid, Ptolemy)

the nature of light. For this I use Table 1, an outline, in a somewhat adapted form, from a recent survey of the history of optics.[9] The table classifies conceptions of light in Classical Antiquity. Viewed schematically, there were four groups of ideas, distinguishable by the answers they provided to two fundamental questions. The first question concerned the way human beings perceive objects: Either the objects have an effect on the eye, or the eye has an effect on the objects. The second basic question concerned the active involvement of a medium between eye and object in the process of seeing. The four 'pure' conceptions consisted of combining pairs of answers. Euclid, Ptolemy, and the Stoics held a theory of 'eye rays', in which the eye scans the objects. For the first two the medium had no part in the process, whereas the Stoics believed that the eye rays were propagated with the aid of the medium, which for them was the air. By contrast, Aristotle assumed that objects acted on the eye via a medium, the 'potentially transparent' that became 'actually transparent' through the action of light-giving objects. Light was a property of the transparent medium, rather than a substance. A different theory was held by the atomists (Leucippus, Epicurus, Lucretius), who posited that an object emitted atoms that constituted a representation of the object. There was no active role for a medium in the propagation of the atoms; on the contrary, the actual medium, the air, was regarded as a disturbing factor in this process.[10]

Theories involving eye rays were largely ignored in the seventeenth century,[11] leaving only two theory groupings: the emission group (with no action from the medium) and the medium group (with objects acting on the eyes via a subtle medium). Pierre Gassendi, who was of great importance for the revival of atomism at the beginning of the seven-

Cambridge University Press
978-0-521-40471-6 - Optics in the Age of Euler: Conceptions of the Nature of Light, 1700-1795
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Excerpt
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teenth century, was a representative of the emission group. Harking back to Epicurus, he put forward an emission hypothesis, in contrast to Aristotle's medium hypothesis. In the eighteenth century Gassendi's name was sometimes cited in connection with the emission group, but by then this conception of light had become more closely associated with Newton. René Descartes, who, like Gassendi, held a corpuscular world-view, was the most significant representative of the medium group. Since his name was also cited a great deal in the eighteenth century, the survey in Chapter 3 of the theoretical traditions in physical optics of the period 1700–45 will begin with Descartes' and Newton's contributions.

A great deal of confusion also arises from the use of the term *theory* by historians. The term is used in such different instances as Newton's 'optical theory' in the Queries, Willem Jacob 's Gravesande's theory of light, and 'the emission theory in the eighteenth century'. Taking these in order, we are dealing with a basic hypothesis, with several suggestions for elaborating upon it; a systematically organised theory that is to a certain extent complete; and a theoretical tradition consisting of a succession of various hypotheses and theories with a common basic idea underlying them. In order to clarify the situation, I distinguish among *hypothesis*, *theory*, and *tradition* in the above examples, and I shall do so, too, in the following chapters.

Development within a theoretical tradition is frequently noncumulative. Huygens' pulse theory thus occupies an isolated position within the medium tradition during the eighteenth century, and only at the beginning of the nineteenth century was Fresnel to continue and improve upon Huygens' specific approach. The remainder of the medium tradition in the seventeenth and eighteenth centuries reveals a greater coherence. Descartes' 'pressure hypothesis', Nicolas Malebranche's detailed pressure hypothesis, Johann II Bernoulli's 'fibre theory', and Euler's wave theory have more in common than merely the basic idea of the medium tradition. This is not to say that there were no significant differences of conceptions and approaches. It is precisely in order to emphasize this aspect that these hypotheses and theories are not regarded as examples of one and the same theory, but rather as distinct parts of a theoretical tradition.

A final point concerned with the use of the word *theory*, deserves our consideration: As there is a difference between a description of the phenomena and their causal explanation, so, similarly, there is a difference between a descriptive and an explanatory theory.[12] In the eighteenth century such a distinction was both made and generally accepted. Thus, geometrical optics, the mathematical theory of the passage of rays through mirrors and lenses, was considered to be a theory that provided no role for the physical cause or nature of light: The passage of rays remained the same, whether light was explained by the emission of particles or by motion within a medium. Another theory with descriptive status in the eighteenth century, one that will be discussed several times in this study, is Newton's theory of colours. Newton claimed in 1672 that he had derived the theory solely through experimentation. He therefore believed, somewhat controversially, that his theory of colours was entirely independent of a causal hypothesis on the nature of light. At that time he preferred not to give an explanation of colours based on physical hypotheses. After some initial opposition in the discussion, Newton's epistemological claim was accepted. That meant that his emission hypothesis of light and his theory of colours were regarded as two distinct elements in his optical work: The first – the explanatory hypothesis – could be rejected, for example, whereas the second – the descriptive theory – was accepted.

Following these remarks on terminology, it is easier to give an explanation of the arrangement and the main propositions of this study.

Chapter 2 provides an outline of Newton's new theory of colours and an analysis of the contemporary discussion of this theory. The German reception of his doctrine of colours is then described in greater detail. In the period 1672–c. 1720 the antipathy between the emission and medium traditions was overshadowed by discussion of Newton's theory of colours, which was soon to be separated completely from the debate on the physical explanation of light and colours. The reception accorded to Newton's theory of colours in Germany confirms the latter suggestion.

In Chapter 3 the development of the emission and medium traditions from the end of the seventeenth century to the middle of the eighteenth is outlined. The thought of a number of prominent figures is discussed, and consideration is given to the arguments for each theoretical position and against the opposing positions. This chapter includes the thesis that the opposition between the emission and medium traditions only increased slowly, and that only with Euler, in 1746, did it acquire the form that present historiography considers to have existed some seventy-five years before that date.

Chapter 4 is entirely devoted to Euler's wave theory. First of all, his theory is located within the medium tradition. Next comes a discussion of Euler's general arguments for and against emission and medium conceptions of light. Finally, some of his fundamental theoretical points are analysed in detail. It is suggested in this chapter that Euler was the first optical theorist to put forward a fairly complete and influential *wave* theory, that is, a medium theory of light including periodical waves; that in doing this he was, in a very general sense, building upon foundations that Huygens had laid, while at the same time rejecting some of Huygens' basic ideas; that the cool reception accorded his wave theory by his Berlin colleagues resulted in the influential first chapter of Euler's principal work on physical optics (the 'Nova theoria lucis et colorum'), in which he drove home the antipathy between the emission and medium traditions through a comprehensive analysis of both; that Euler's greatest conceptual contribution lay in the anchoring of the concept of frequency in the medium tradition, and that the related climax of this theory was found in the hypothesis – later disproved – of the existence of 'undercolours'. (Euler held that there were colours with frequencies higher and lower than those in the solar spectrum; I have chosen to name them overcolours and undercolours, by analogy with overtones in music.)

Chapter 5 treats of the German debate on the nature of light that followed the publication of Euler's wave theory. During most of this debate, which lasted for about fifty years, the supporters of a medium theory outnumbered the defenders of an emission theory. By way of introduction there is an outline of the situation circa 1740 and of the support enjoyed by the different light theories in the subsequent half century. Description and analysis of the content of the debate comprises the main part of the chapter. Included are two early contributions to the discussion, in which Euler's general arguments were dealt with one by one. As in the rest of the debate, the details of his wave theory were not taken into account. The first contribution repudiated Euler's line of argument, whereas the second accepted it. Clearly Euler's arguments were unable definitively to conclude the debate on light. A detailed treatment of the discussion of two physical phenomena follows. The first phenomenon is the rectilinear propagation of light, for the major objection to the medium theories was that their explanation of this phenomenon was incorrect. The theoretical ideas and new experiments advanced in connection with this aspect of the discussion failed to close the debate on light. The same applies to the second physical phenomenon considered in the debate: the experiment on 'grazing light rays' (rays that travel close to the surface of glass, for example), which played a modest but intriguing role in the German discussion. The debate changed its character in the mid-1770s, when interest was aroused in a phenomenon with both physical and chemical aspects: phosphorescence. Experiments on the absorption and production of coloured light by phosphorescent substances stimulated a discussion in which Euler participated. However, the experiments on phosphorescence could not end the debate. The debate only concluded after around 1789, when the chemical actions of light (the formation of oxygen by green foliage and the blackening of silver salts, for example), which had been extensively investigated shortly before, were added to the discussion agenda. The conclusion was unexpectedly rapid and complete. The medium tradition lost its dominance within a few years and was replaced by the emission tradition. Since Germany joined in the international pattern of the history of optics around 1795, that year provides a natural end-point for this study.

Chapter 6 constitutes an epilogue, although not in the usual sense, as it contains no outline of developments within the field of optics after 1795. It is presented as an epilogue in the *historiographical* sense. Set against the background of a number of conclusions from the previous chapters, a historiography of science for the seventeenth and eighteenth centuries is outlined. This suggestion draws on the work of Thomas Kuhn on the historical development of the physical sciences, but it also signals a fundamental change to his schema.