Chapter 2
Christoph Scheiner's *The Eye, that is, The Foundation of Optics* (1619): The Role of Contrived Experience at the Intersection of Psychology and Mathematics

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2.1 Introduction

This chapter examines the Jesuit polymath Christoph Scheiner's (1573–1650) 1619 work, *Oculus hoc est: fundamentum opticum*, or *The Eye, that is, the Foundation of Optics* (hereafter *Oculus*). I consider two broad issues from the history and philosophy of science.[1] The first has to do with the problem of establishing first principles in natural sciences based on experience and experiment. Early accounts in the history and philosophy of science, attempting to understand when and how modern experimental science arose, took the sixteenth and seventeenth centuries as a turning point: Aristotelian natural science, while at least nominally based on sense perception, supposedly neglected, discouraged, or was outright hostile to experimental investigation. The new science, developed by figures such as Francis Bacon, Galileo Galilei, and others, was said to be responsible for reforming natural philosophy and placing natural science on firm experimental foundations, and it did so by rejecting Aristotelianism. Although it is not false in every respect, this picture has proven inadequate, and recent attempts to understand Aristotelian contributions to seventeenth-century developments in natural science have helped to remedy this oversimplified account. More yet needs to be done, however.

The Jesuits have been of particular interest in this regard given their pedagogical influence in the seventeenth century, along with the sheer number of treatises they produced. Nevertheless, lingering assumptions about the supposed anti-experimentalism embedded in Aristotle's works—or Aristotelianism, however

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understood—have colored these accounts. Looking at Scheiner's *Oculus*, I argue that the concern with the problem of establishing the foundations of natural science on the basis of experiments and contrived experiences was not confined to the *novatores* such as Galileo; it appears to have been a general project. Furthermore, I argue that Aristotelianism *per se* presented no in-principle obstacles to the use of contrived experiences and experiments in establishing the first principles or axioms of a science. Finally, I suggest that Paduan Aristotelianism was an important influence on Scheiner. Although Ernst Cassirer (1906, 139), John Herman Randall (1940), and others following them have argued, controversially, that the Paduan professor in logic and natural philosophy Jacopo Zabarella was a key figure in the development of the "scientific method," I propose that Scheiner's use of experience and experiment to establish first principles in the science of optics was inspired more by anatomists such as Hieronymus Fabricius ab Aquapendente.

The second issue I touch on has to do with the problem of how to incorporate, into natural science, contrived first-person experiences and experiments, in particular judgments about visual phenomena such as color, distance, number, shape, and so on. Much of the history and philosophy of science, particularly for the early modern period, has focused on how experiments were used as evidence for or against theories together with the problem of establishing public facts via observation and experimentation. Such scholarship centers on the development of the concept of natural law and has made connections between concepts of public evidence in legal contexts and experimental evidence in scientific communities. In contrast, what we might call "self-perceptual" experiments do not fit this model of public evidence. These kinds of experiments or contrived experiences belong more to the history and philosophy of psychology than to physics. Indeed, from antiquity through the early modern period the discipline of optics was a demonstrative science that drew its principles in part from the science of the soul (what today we might classify as psychology), which was itself understood as a branch of, or topic within, natural philosophy. (As a so-called middle science, optics also drew its principles from geometry.) Prior to and largely during the seventeenth century, optics was primarily the science of seeing, not the science of light (Smith 2015). Examining Scheiner's *Oculus* with this background in mind thus contributes to questions of experimental rigor and control in the history of psychology, the senses, and the sensibles (e.g., light, color, and distance perception) in the *longue durée.* Scheiner's *Oculus* and other contemporaneous works, such as François de Aguilon's 1613 *Opticorum libri sex*, are part of a history that begins in antiquity and connects to key works in physiological optics by Hermann von Helmholtz and Ewald Hering in the nineteenth century.

To address both of these issues—how to establish first principles on the basis of experience and experiment, and how to deal with contrived first-person experiments—it is necessary to address anachronistic readings of Aristotle's *Posterior Analytics* and their influence on the historiography of the Scientific Revolution. The subject of the *Posterior Analytics* is demonstration, or "a deduction that produces knowledge." This work was carefully studied in Aristotelian (including Jesuit) education of the early modern era. It ends with a notoriously brief chapter (II.19) that offers an account of how the first principles of a demonstrative science are grasped. I follow several recent scholars who have argued that we should not understand the *Posterior Analytics*—particularly II.19—as a treatise on epistemology, i.e., an account of how to justify knowledge claims. Rather, II.19 is better understood as a general psychological *description*, beginning with sense perception and ending with the comprehension of universal first principles. Because each science had distinct methods for arriving at first principles, an account of how to justify the foundations of that science, according to Aristotle, belonged at the beginning of such treatises and not in a very general account such as the one given in the *Posterior Analytics*.

I argue that this reading is closer to the interpretation of the *Posterior Analytics* in the early modern period as well, particularly in light of the so-called "Aristotle Project" in late sixteenth-century Padua that revived Aristotle's science of animals and the animal soul. This view has major ramifications for understanding how authors, such as Scheiner, used experience and experiment in the process of grasping first principles. That process for Scheiner is not a matter of stripping away the particularities of any individual sense experience in order to arrive at the universal core of a sensation (i.e., it does not directly invoke a realist position with regard to universals); nor is it a matter of accessing *a priori* universal first principles in a Neoplatonic fashion. Finally, it is not a matter of invoking universal "common sense" observations as a starting point. Rather, Scheiner is influenced by the anatomical tradition according to which the reliability of one's determination of the properties, activities, and purposes of the universal anatomical part arises from the combination of skill at dissection, long experience, and deft engagement with the accounts of anatomical authorities, both ancient and contemporary. It involves being able to demonstrate one's anatomical findings, ideally in person, and to argue convincingly from those observations.

In short, in their attempts to understand how experience and experiment were incorporated into the sciences in the myriad ancient, medieval, and renaissance Aristotelianisms, historians and philosophers have looked in the wrong places. Many supposed problems that experiment raised for Aristotelian science simply disappear if we do not assume that historical actors took II.19 in Aristotle's *Posterior Analytics* as a work of epistemology; examining specific scientific treatises to assess how Aristotle and Aristotelians justified the foundations of their sciences is the better route. We can read Scheiner's *Oculus*, then, as a treatise on how, in a (broadly) Aristotelian treatment of vision science, one starts with sense perception, forms memories, gathers these memories to form experiences, and finally how from that state of *being experienced* or *having experience* one securely grasps first principles. This is precisely the title of his work: *The Eye, that is, the Foundation of Optics*. I show here that Scheiner understands the foundation for the science of optics to consist of dissecting the eye, performing experiments and generating contrived experiences to understand the actions of the eye (primarily sight, a complex action), and appealing to particular (and even unique or singular) observations and experiences of others. That is, early in the process of developing Aristotelian experience, Scheiner requires the reader to perform contrived experiences and experiments to become truly experienced, and being experienced includes having the written records of an exhaustive body of experience to hand. Only after all of this has been done can one combine these experiences with geometrical knowledge in order to grasp the first principles or axioms of optics. Notably, although he accepts Kepler's revolution in optics, which moved the site of sense perception from the lens to the retina, Scheiner retains the traditional axioms of optics. As Scheiner (1619, 124) states at the end of Book III part 1, and shows in Book III part 2, "All the axioms reported by Euclid's still hold in the strictest rigor."

The plan for this chapter is as follows. I first briefly review the historiography of early modern experience and experiment. Because he has addressed these issues in the most detail, is considered an authority on these matters, and is one of few scholars to have analyzed Scheiner's *Oculus* at length, I focus on Peter Dear's work. In this section, I also show the influence of Paduan anatomy on Scheiner. I next discuss Aristotle's *Posterior Analytics* and the issue of first principles in pre-modern and early modern optics, followed by a brief introduction to the science of optics at the beginning of the seventeenth century. Following this, I analyze the use of contrived experiences and experiments in Scheiner's *Oculus*.

2.2 Historiography

To begin, however, a short biography of Scheiner is needed; for more detail, see (Shea 2008) and (Daxecker 2004). Scheiner was born in Wald, a small village in Bavaria that was active in the Counter-Reformation, including a strong Jesuit presence. He was educated by Jesuits and joined the Order in 1595, studying mathematics and philosophy in Ingolstadt from 1600. He later also studied theology there, beginning in 1610. He is best known today for his observations of sunspots in 1611, and for his priority disputes with Galileo over their discovery as well as debates over their nature. He published many other works on mathematics and was an accomplished inventor as well, writing treatises on instruments he created including the pantograph. Another notable publication is his later *Rosa ursina sive sol*, which includes a detailed account of his sunspot observations, comparisons between the human eye and a telescope, a description of his helioscope, and many other astronomical observations and arguments. In this chapter, however, we are mainly concerned with his *Oculus*, which was first published in 1619 in Innsbruck, and reprinted in 1621 in Freiburg im Breisgau and in 1652 in London.

Questions surrounding experience and experiment were the bread and butter of the historiography of the Scientific Revolution as the disciplines of the history and philosophy of science were being formed in the first two-thirds of the twentieth century. Some specific narratives about experience and experiment—particularly the failure of Aristotelian science to use experiments to either ground or test claims—became commonplace in mid-twentieth century accounts. I pulled at random an early Scientific Revolution textbook from my shelf as an example; thus Charles Gillispie (1960, 12–13):

> [Aristotelian science] started from experience apprehended by common sense, and moved through definition, classification, and deduction to logical demonstration. Its instrument was the syllogism rather than the experiment or the equation. […] For however congenial Aristotelian physics was to the self-knowledge of the minds that elaborated it, nature is not like that, not an enlargement of common sense arrangements, not an extension of consciousness and human purposes.

Much has been done since to challenge such blanket statements (Newman 2006; Ragland 2017), but Peter Dear's work is arguably the most influential attempt to understand the Jesuit Aristotelian approach to experience and experiment in the seventeenth century. His writings remain authoritative in some respects, and he is one of few to have analyzed Scheiner's *Oculus* in detail. I will therefore quote him at length. Dear (2006, 109) writes:

> For Aristotle, a science of the physical world should, ideally, take the form of a logical deductive structure derived from incontestable basic statements or premises. The model for this was the structure of classical Greek geometry as exemplified in Euclid's *Elements*. […] In the case of sciences that concerned the natural world, however, such axioms could not be known by simple introspection. In those cases, the axioms had to be rooted in familiar and commonly accepted experience.

For Aristotelians, it seems, it is only communally agreed-upon experiences that can serve as the basis for a deductive science (Dear, 109, emphasis in original):

> This kind of experience, therefore, was of universal behaviors rather than particulars: The sun *always* rises in the east; acorns *always* (barring accidents) grow into oak trees. Singular experiences … were more problematic because they could only subsequently be known by historical report, as something that had happened on a particular occasion. They were thus unfit to act as scientific axioms because they could not receive immediate free assent from all: Most people had not witnessed them.

He continues (110):

> Aristotle's natural philosophy was especially concerned with 'final causes,' the purposes or ends toward which processes tended or that explained the conformation and capacities of something. […] Active interference, by setting up artificial conditions, would risk subverting the natural course of things, hence yielding misleading results: experimentation would be just such interference. […] To the extent that Aristotle's natural philosophy sought the final causes of things, and thereby to determine their natures, experimental science was therefore disallowed.

Several clear counterexamples to this last statement have come to light since 2006. Examples are the physician and chymist Daniel Sennert (Newman 2006, 86–125) and the physician and anatomist William Harvey (Lennox 2006, 5–26; Distelzweig 2013, 151–69; Goldberg 2016; Lennox 2017, 151–68).[2] Both were self-professed followers of Aristotle, something we see both in the intellectual content of their writings, and also, most importantly, in their methods for investigating nature (Klein 2014, 136–37; Ekholm 2011, 45–46). These included performing experiments as self-professed Aristotelians to discover material, efficient, formal and—especially

[2] On the early modern term chymistry, distinct from both medieval alchemy and modern chemistry, see Newman and Principe (1998).

in anatomy—final causes. Based on these figures alone, we see that the position held by Dear and others, namely that experience and experiment were somehow at odds with the search for Aristotelian final causes, is false, particularly for the science of animals.

Dear offers a complicated story of a difficult transformation within Aristotelianism, spearheaded by Scheiner and other Jesuits, to accommodate Aristotle's writings to experimentation and mathematical physics. In a seminal article on the Jesuit contribution to the role of experience and experiment in seventeenth-century investigations of nature, he describes a philosophical-methodological puzzle faced by the Jesuits as they attempted to incorporate experimentation and mathematics into natural philosophy (1987, 160):

> The employment of constructed experiences in the mathematical sciences threatened to violate not only the requirement that scientific premises be evident, but also the strict artificial/natural distinction at the heart of the Aristotelian world-view.

While Dear has perhaps tempered his opinion on this issue since, it is still clearly present in his writings 20 years later. Moreover, he expresses an attitude common since the mid-twentieth century at least. Even if it is no longer taken for granted by many early modern scholars, the narrative persists among non-specialists as a key component of the scientific revolution.[3]

But what, for Aristotelians, was the artificial/natural distinction? It was simply to identify whether the cause of some change—local motion, alteration, or substantial transformation—can be found in the innate capacities, or the nature, of the substance in question, or whether one ought to look outside that substance for a cause. Aristotle in the *Generation of Animals* (735a2–4) writes: "For the art is the starting-point and form of the product; only it exists in something else, whereas the movement of nature exists in the product itself, issuing from another nature which has the form in actuality."[4] Aristotle's example in the *Physics* is that of a wooden bed: if we plant a wooden bed frame and it starts to sprout on its own, it will grow into more wood, i.e., a tree, not into more beds (193b7–193b12). The wood has the nature of a tree, and if moved by that nature it changes insofar as it has the innate capacities of growth, nutrition, and reproduction, all of which are guided by the *telos* of becoming a flourishing tree. But the wood is made into a bed, with the ability to promote good sleep, by art—that is, by an external force moving it to ends external to the tree or wood itself. In another example used by Aristotle, if we suppose (impossibly) that an axe was a natural substance with a soul, then it would be able to achieve its final cause—chopping wood—owing to its own internal nature, rather than, as a product of art, only via an external mover. Natures are principles of motion

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[3] The literature on this topic is extensive, and I do not delve too deeply into it here. For a sustained argument against the traditional account of the art/nature distinction, see Newman (2005), especially chapter 5. On the epistemology of early modern meteorology, to which the traditional account of Aristotle's art/nature distinction cannot do justice, see Martin (2011), especially chapter 1.

[4] All translations of Aristotle are from the Barnes edition (Aristotle 1984), which I cite only by Bekker number. Unless otherwise noted, translations of all other works are my own.

and rest, and they are in a sense ontologically primitive in Aristotelian philosophy. They describe inward impulses moving substances toward particular ends. On the other hand, the ends for artificial substances, and the activities needed to achieve these ends, come from outside.

Seventeenth century anti-Aristotelians called such natures "occult," and so too did some Aristotelians. But on a fundamental level it is difficult to see why the notion of Aristotelian natures would be an obstacle to experimental investigation—no more, that is, than experimental investigation within other philosophical and methodological frameworks. The most famous seventeenth-century proponent and theorizer of the experimental method, Francis Bacon, sought through his new logical tool for scientific investigation, the *Novum organum*, to discover the basic natures in Nature, natures arguably no less occult than those the Aristotelians posited. As Bacon famously wrote at the beginning of the *Novum*'s first book (Bacon 2004, 65): "As for works man can do nothing except bring natural bodies together or put them asunder; nature does the rest from within." Now Bacon thought that such basic natures were few and combined to form new natures in the way letters combine to form words; in contrast, Aristotle and most of his followers seemed happy to admit as many natures as there are species of plants and animals. Nevertheless, it is not obvious that the art/nature distinction in Bacon offers any more or fewer obstacles to experiment than the art/nature distinction held by the Aristotelians he attacked.[5] Dear and others argue that artificially constructed experiments or experiences do not reveal the normal course of nature. But although Aristotelians indeed held that one can only have a natural science of things that happen always or for the most part, this in no way entails that Aristotle or Aristotelians had any issue with experimentation *per se*. One must simply ensure that one's experiments shed light on what happens in nature always or for the most part—a requirement, it seems, for any investigator of nature.

It is difficult to find early modern Aristotelians cautioning against experimentation in general or discussing the problem of singular experiments. We do find a sort of example later in the century, by the philosopher Giovanni Maffei in Pisa writing to the Grand Duke Ferdinand II around 1670.[6] In defending Aristotle against the experiments of Galileo, he writes (Galluzzi 1995, 1329):

> [Note that] experience is fallible and dangerous, as Hippocrates holds, and that the intellect needs to correct the sense when it knows that [what is sensed] is not the case; I also say that in order for an evident proof to be drawn from experience, it is necessary that the effect experienced is known, time and time again, to be uniform, since one sensation of a particular effect is not enough from which to derive a universal proposition, but long observation is necessarily required, made up of many, many experiences, and from this used as a scientific foundation.[7]

[5] For a thorough discussion of the art/nature distinction in Bacon, see Newman (2005, 256–71).

[6] Thanks to William Newman for bringing this to my attention.

[7] "Alla prima dubitatione rispondo che l'esperienza è fallace e pericolosa al sentire d'Hippocrate e che deve correggersi dall'intelletto il senso quando conosce ciò che non è; dico inoltre che acciò che da quella si cavi una prova evidente è necessario che l'effetto sperimentato sia più e più volte

He likewise cautions against confusing natural causes, which operate spontaneously, with artificial ones, and warns against those who believe "that nature operates similarly when left free, as when it is constrained and deprived of its natural ability by art" (1329). His criterion, he mentions several times, is uniformity. Here, then, we have a polemical attack by a Catholic natural philosopher against the "Democritean" doctrine of Galileo, lamenting in the second half of the seventeenth century that Aristotelian doctrine is not being taught properly in the schools, and that Aristotelianism, even if imperfect, is being replaced by flimsy and empirically unsupported philosophies: "To extract a universal proposition from many particulars, one needs the eyes of an Argus in quantity and of a Lynceus in perspicacity, and such eyes are certainly not the eyes of the common intellect" (1329). What we see in these remarks, however, is primarily that Aristotelians and *novatores* such as Galileo had different opinions about which basic motions existed *by nature*; apart from ad-hominem attacks on the carelessness of the *novatores*, it is hard to read much else here. Singular experiments that cannot be replicated are always suspect; determining whether an observed effect is genuinely attributable to nature or merely an artifact of the experimental set-up is always a problem needing resolution. Whether there are indeed such things as irreducible Aristotelian natures, or whether those supposed natures are reducible to other (perhaps mechanical) causes, is a separate issue.

I would argue that the contribution by Arnet to Chap. 10, this volume, for instance—where twentieth-century attempts to study learning in rats led to interventions that arguably distorted the learning capacities of the rats—is, metaphysical issues aside, perfectly comprehensible if reframed in Aristotelian terms. In Arnet's study, artifice with the aim of "control" destroyed certain capacities of the rats in the experiment, rendering them imperfect (as Aristotelians would frame the alteration) and thereby unable to move toward their goals as rats typically do. Thus certain experiments did not, in fact, reveal the aspect of the rat's nature that the experimenters believed they were investigating. I am not proposing we ought to reframe the episode in this way; I am suggesting only that Aristotelianism was highly adaptable, and that in many cases little is gained by setting it in opposition to modern science by default.

Paduan anatomists around the turn of the seventeenth century offer good examples of early modern Aristotelians who engaged with experiment and contrived experience, with Hieronymus Fabricius ab Aquapendente (1533–1619) being perhaps the most influential on vision and the eye (1600).[8] Paduan anatomists are worth examining, moreover, because their treatises on the eye influenced Jesuit optics, including Scheiner in his *Oculus* (1619, 20, 119), and because their revival of the

conosciuto uniforme, non bastando una sensatione d'un effetto particolare per cavarne poi una propositione universale, ma si richiede necessariamente un'osservatione lunga, fatta in molte e molte esperienze, e di quella valersene per fondamento scientifico."

[8] We also see a similar approach to anatomy in his student and eventual rival in Padua, Julius Caserius (1609), as well as those trained in Padua around the turn of the century, such as William Harvey.

"Aristotle Project" for studying animals and the universal animal soul contained explicit Aristotelian methodological precepts, specific to the study of animals, developed from Aristotle's *History of Animals, Parts of Animals,* and *On the Soul* (Cunningham 1985). To answer the question, "What is the capacity for sight in animals?" these anatomists give the history (*historia*), action (*actio*), and usefulness (*usus*) of the parts of the eye. This process begins by carefully dissecting as many different animals as possible, with as many individuals of each as possible. (These writers do not specify an ideal number of cases; more is simply better.) This experience provides the basis for the *historia*, also referred to as *structura* or *fabrica*, of one's investigation into the nature of vision; based on criticisms anatomists made, as well statements on why their own investigations ought to be trusted, we can say that developing anatomical *historia* demands meticulous dissection technique, careful observation using all five senses, and a thorough review and critique of all authorities that have investigated the eye.

Next, they look at the activity of vision itself, which necessitates investigations into the nature of light and color, whether rays might be emitted from the eye, which parts of the eye actively receive impressions from visible things, how the soul, spirit, or visual faculty receives or generates visual information, and so on. That is to say, the *actio* section contains arguments for a theory of vision along with a theory of light and color. Finally, they determine the *usus* or *utilitates* of the parts of the eye, a project which is also framed in terms of Aristotelian final causes. This account of the purposes of the parts—like the shape, size, situation, color, texture, refractive power, color, etc., of the crystalline lens vs. the vitreous humor vs. the aqueous humor—necessitates discussing rival theories of vision. By taking for granted that the parts of the eye do have final causes (they exist for the sake of vision), and by combining this view with a theory of light and color previously established in the *actio* section, the anatomist can be called on to perform experiments that provide evidence for or against various theories of vision.

Fabricius conducted simple, public experiments on how the crystalline lens, separated from the living animal, refracts light and focuses rays into a cone whose point would lie somewhere within the vitreous humor. These he performed to refute extramissionist (largely Galenic) theories of vision (1600, 102–3), and also to challenge certain aspects of perspectivist optics. The Aristotelian logician and natural philosopher Zabarella (who also wrote a commentary on Aristotle's *Posterior Analytics*) also saw these experiments, suggesting that they were performed publicly. In his natural philosophy textbook *De rebus naturalibus*, Zabarella wrote as a witness to a singular event: "I saw the crystalline separated from the other humors in a dissection of the eye, which when placed near a small lit candle was made to shine all over…" (1590, 632–33). Like Fabricius, he used these experiments to argue against Galenic theories of vision. Via his careful description of the sizes, shapes, and relative refractive powers of the parts of the eye, all discovered by the anatomist's knife, Fabricius also offered an empirical refutation of certain key aspects of the mathematical optics of the perspectivists, such as Alhazen, Witelo, and Peckham. These observations and experiments were performed with dead eyes that lacked the animating nature of a living eye—indicating that the eyes were not in their "natural" state. The experiments also relied on the assumption that everything in the body was fabricated for the sake of specific ends—i.e., that final causes exist, and indeed are prior to the body's matter—in order to argue against accounts of vision that rendered the shapes, sizes, temperaments, relative positions, etc. of certain parts of the eye purposeless. Thus, at this time, assuming that the parts of the body possessed final causes improved, rather than hindered, the effectiveness of Fabricius's and Zabarella's arguments, which were empirical and to some extent experimental (Baker 2019, 137–42).

Although the literary and investigative framework for Fabricius's project—*historia, actio, usus*—was largely Galenic, he followed Aristotle's account in the *Posterior Analytics* for how to arrive at first principles i.e., the faculties, capacities, or natures of the parts of the body (1600, unnumbered prefaces to *De visione* and *De voce*). Many other anatomists drew on Aristotle's *Posterior Analytics* as well, including, most famously, Fabricius's student William Harvey (Cunningham 1985; Goldberg 2012, 214–32; Distelzweig 2013, 13–151).

2.3 Aristotle's Posterior Analytics, First Principles, and Early Modern Mathematical Optics

It may still be the case that, as Dear and others claim, there is something about astronomy, optics, mechanics, and other sciences—sciences that combined mathematics and natural philosophy—that rendered experiment and contrived experience problematic for Aristotelians. To see why this is not the case we should review Aristotle's notoriously brief account in the *Posterior Analytics* of how to establish first principles in a science.

Aristotle held that "All teaching and all intellectual learning come about from already existing knowledge" (*Posterior Analytics,* 71a25–71a30). Much of the *Posterior Analytics* is concerned with scientific demonstration, or how new knowledge can be derived from previously existing knowledge, particularly in the natural sciences. Crucial to his account, therefore, is the problem of establishing *first principles*, which cannot be demonstrated from previous knowledge owing to the threat of infinite regress. Aristotle's solution comes in the final chapter of the second book. The puzzle about inquiry in the *Meno* is first summarized: if we have knowledge of first principles innately, then it seems absurd that we would not recognize that we have such knowledge, which is even more precise than knowledge arising from demonstration. If we do not have innate knowledge of first principles, then it seems impossible that we can acquire knowledge of them without preexisting knowledge, that is, it seems that knowledge would arise out of nothing. Aristotle resolves this puzzle with the potency-act distinction: we evidently have an innate capacity or potential for such knowledge, even if we do not have that specific piece of knowledge in actuality: "And *this* evidently belongs to all animals; for they have a connate discriminatory capacity, which is called perception" (99b35–100a2). (Here Aristotle is using "knowledge" very broadly. The sort of knowledge that an animal can potentially have depends on their other cognitive capacities, and so an animal without the capacity for memory can only "know" in the sense of directly perceiving particulars.) In human beings, sensation leads to memory and many memories lead to experience, which he says results in "the whole universal that has come to rest in the soul (the one apart from the many, whatever is one and the same in all those things)." This leads to skill, in the case of practical arts, or understanding (*nous*) of first principles in the case of speculative disciplines (100a10–100a14):

> Thus the states [of comprehending first principles] neither belong in us in a determinate form, nor come about from other states that are more cognitive; but they come about from perception—as in a battle when a rout occurs, if one man makes a stand another does and then another, until a position of strength is reached. And the soul is such as to be capable of undergoing this.

The primitives or first principles arise from a sort of induction. This account seems to be one provocation for Francis Bacon's criticism of the Aristotelian logic or method for investigating nature, which was that they fly too quickly to first principles ("axioms" in Bacon's terminology). But while Aristotle's remarks here are brief, there is no reason to conclude that all Aristotelians held that the process of grasping first principles is itself brief or uncomplicated. As Aristotle mentions time and again, becoming a person of experience is a long process.[9]

In the twentieth century, this passage, and the *Posterior Analytics* overall, were read as a treatise on epistemology: Aristotle was supposed to be giving an account of how knowledge claims are justified. But Aristotle's use of *episteme* has at least two senses here, as either a body of knowledge or as a cognitive state. Taking the second sense as primary, the *Posterior Analytics* can be read, not as an account of the justification of knowledge, but as an account of how demonstration works as a form of explanation (Salmieri et al. 2014, 2–3). Aristotle's notoriously brief treatment in book II chapter 19, then, can be seen as just a highly general account of the psychological act of acquiring first principles of a science, or a description of how we move from sensation to first principles; it does not offer an epistemological justification for the truth of those principles (Aydede 1998, 38–39). Justification is therefore not offloaded to *nous* in some mysterious way, and the act of intuition (i.e., of grasping universal first principles as the result of sufficient experience) is not, in this view, assumed to be infallible (Aydede 1998, 19). Rather, the justification of the first principles of a science requires a case-by-case approach, and such a justification properly belongs at the beginning of the treatises of each specific science (Salmieri et al. 2014, 33). This is arguably what we see in Aristotle's works, where the norms of inquiry, including the establishment of first principles, are specific to each domain (Lennox 2011, 23–46; 2021).

[9] E.g., 316a5–10, 980b26–981a12, 1142a12–21.

Aristotelians such as Scheiner, I argue, held that the process of acquiring the requisite experience to grasp first principles is also not simple or straightforward.[10] In the early modern period, whether we examine written statements by historical actors or reconstruct actual practices, experimentation hardly seems barred from this experience-gathering phase in natural science. This would include sciences that drew on principles of natural philosophy, such as optics.

2.4 The State and Scope of Optics Circa 1620

In the first half of the seventeenth century optics was still fundamentally a science about understanding and explaining first-person visual experience, rather than understanding light and image formation. That is, geometrical rays were investigated largely to make sense of first-person visual experiences. This was the understanding of optics at least until Kepler, as A. Mark Smith has shown (2015, ix):

> For the vast majority of its history, the science of optics was aimed primarily at explaining not light and its physical manifestations, but sight in all its aspects from physical and physiological causes to perceptual and cognitive effects. Consequently, light theory was not only regarded as subsidiary to sight theory but was actually accommodated to it.

Prior to Kepler, the lens or crystalline humor was believed to be the primary seat of visual sensation. Smith argues that Kepler's retinal theory of vision transformed (at least eventually) optics into its modern form. But even though Kepler's work contributed to this reconfiguration of optics' scope, I argue elsewhere (following Antoni Malet) that even as late as Descartes's 1637 *Dioprique* this inversion was not yet accomplished—that the goal of optics was still largely to understand first-person visual perception and not reflection, refraction, and image formation (Malet 2005; Baker 2016). Accordingly, to understand Scheiner's *Oculus* in context, we must understand the scope and aim of optics immediately after Kepler's radical work; it will also help to review Descartes's investigations for a fuller view of the approach. I focus here on the order of topics addressed so that we can see how an understanding of light, refraction, ocular anatomy, and the visual faculty came together in seventeenth-century accounts of vision.

From antiquity until the seventeenth century, optics, or *perspectiva*, was often referred to as a so-called "middle" science. It was subordinate to (and thus took its principles from) both natural philosophy and geometry. One goal of optics was to save the phenomena in the most literal sense of that phrase, i.e., "account for the appearances" (Smith 1981). The mathematical cone employed by Euclid and Ptolemy was used to do so (see Fig. 2.1). The postulates in Euclid's optics, for example, are the following (Euclid 1947, 357):

[10] On the notion of experience according to William Harvey, which is similar to what we find in Scheiner (not surprising given the Paduan influence on both), see Goldberg (2016).

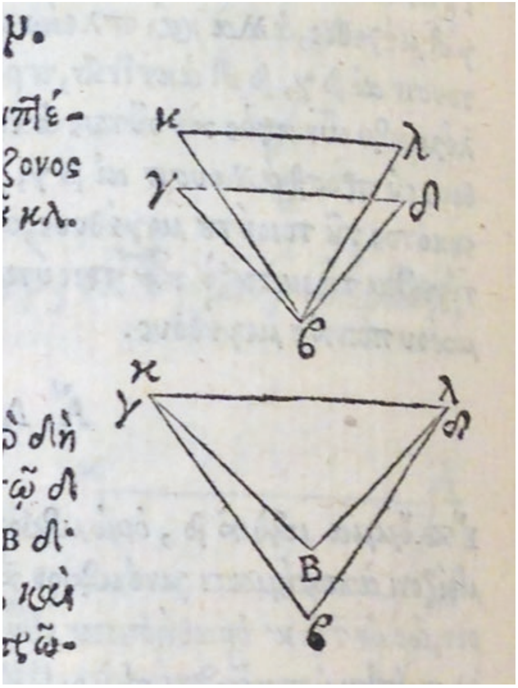

Fig. 2.1 The visual cone model, showing the same size line appearing smaller if it is farther away from the observer (above), and larger as the observer moves closer to it (Euclid 1557, 8)

1. Let it be assumed that lines drawn directly from the eye pass through a space of great extent;
2. and that the form of the space included within our vision is a cone, with its apex in the eye and its base at the limits of our vision;
3. and that those things upon which the vision falls are seen, and that those things upon which the vision does not fall are not seen;
4. and that those things seen within a larger angle appear larger, and those seen within a smaller angle appear smaller, and those seen within equal angles appear to be of the same size;
5. and that things seen within the higher visual range appear higher, while those within the lower range appear lower;
6. and, similarly, that those seen within the visual range on the right appear on the right, while those within that on the left appear on the left;
7. but that things seen within several angles appear to be more clear.[11]

Euclid and Ptolemy both posited an extramitted visual cone, but after Ibn al-Haytham in the eleventh century most perspectivists followed him in accommodating the visual cone to Aristotle's more satisfactory physics according to which the

[11] Note that Burton labels these "definitions," but early modern editions refer to them as posits, suppositions, or axioms. For example, the influential early edition by Jean Pena (Euclid 1557, 4) labels them *posita.*

forms of light and color enter into the eye from without. This synthesis was accomplished, among other things, by positing a very specific, *a priori* geometrical account of the eye, and by locating the seat of visual perception in the crystalline humor. Early modern anatomical investigations of the eye that questioned this geometrical arrangement therefore threatened the visual theory of the perspectivists (Baker 2016).

In this period the order of topics presented any given optical treatise largely tracks the epistemic priorities of the author. The perspectivists begin with an account of light and color, followed by a qualitative account of refraction and an account of sight in direct vision; only after this are we given an account of the anatomy and physiology of the eye needed to accommodate the visual cone (Fig. 2.2). John Peckham's *Perspectiva communis*, the typical introduction to optics from the fourteenth through the sixteenth centuries, can be outlined thus (here I draw primarily from the 1504 Venice edition):

- Book I: Vision by direct rays
  - Propositions 1–27: The properties of light and color and their propagation
  - Propositions 15, 16: Qualitative account of refraction
  - Proposition 28: The manner of direct vision, namely,
  - "Sight occurs through lines of radiation directly [i.e., perpendicularly] incident upon the eye." (5v)

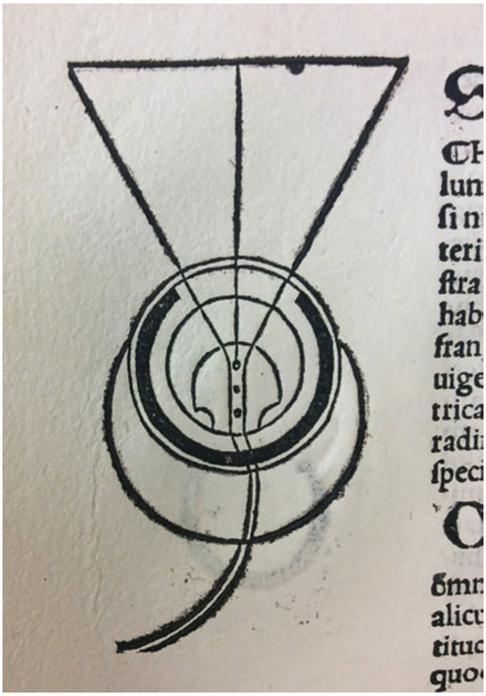

Fig. 2.2 The geometry of the eye accommodated to the intromitted visual cone (Peckham 1504, 6v)

- Propositions 29–46: Anatomy and physiology of the eye and the act of visual perception

  "Visible things are grasped (*comprehensio*) by means of a pyramid of radiation; the certitude of apprehension (*certitudo apprehensionis*) however is made by the axis [of vision] being carried all over the visible." (6v)

- Propositions 47–54: Physical requirements for vision
- Propositions 55–79: Psychology of vision

• Book II: Vision by reflected rays
• Book III: Vision by refracted rays

The works of the other perspectivists—Alhazen, Witelo, and Bacon—give the same order as Peckham's book.

Drawing on recent anatomical investigations, Kepler introduced the retinal theory in his 1604 *Paralipomena ad Vitellionem, quibus astronomiae pars optica traditur*, or *Supplement to Witelo, in which the Optical Part of Astronomy is Given*. Along with Alhazen's *Optics*, Witelo's *Optics* was a standard advanced treatise prior to the seventeenth century. Kepler's argument for the retinal theory begins by establishing thirty-eight propositions about the nature of light and color. Although he claims that they are "among the principles in Euclid, Witelo, and others" (Kepler 2000, 20), their clear Neoplatonic basis would have been controversial for many at the time.[12]

In the second chapter he solves a long-standing problem of pinhole images. In the next he refutes Euclid, Witelo, and Alhazen on the formation of images in mirrors, and in so doing Kepler attempted to place catoptrics, or the mathematics of reflection, on a more secure footing (Goulding 2018). Chapter four tackles refraction in a thorough and sophisticated manner without, however, the benefit of the sine rule of refraction. Finally, in chapter five, he gives first the anatomy of the eye and only then the means of vision, namely, that vision occurs when an inverted image is cast upon the retina in the manner of a *camera obscura*. He argues for this claim using a mathematical account of the path of rays through a transparent sphere—i.e., the caustic of a sphere—then confirms the mathematics with experiments of light passing through spherical urinal flasks. Lastly he shows how these mathematical results demonstrate that the crystalline humor indeed refracts rays such that they bring innumerable cones of rays, sent out from each point in the thing seen and landing on every part of the cornea (there forming the bases of those cones), back to

[12] For example, in establishing the basis for his thirty-eight propositions on rays of light and color he writes, "The spherical is the archetype of light (and likewise of the world)" (Kepler 2000, 19). As one clear example of a controversial position on the nature of light itself, see Proposition 32, "Heat is a property of light" (39). For Kepler's Neoplatonic account of light, see Lindberg (1986). Kepler's theory of light cannot easily be captured here. The introduction and first chapter of his *Paralipomena* dedicate thirty-eight propositions (plus lengthy corollaries) to establishing his mathematical-physical-theological account of light and color, and this is followed by an attack on Aristotle's account of light, as Kepler interpreted it. The latter, ignoring entirely nearly 2000 years of commentary, would hardly have been convincing to scholastic Aristotelians. For a more detailed account of Kepler's Neoplatonism, influenced by Proclus in particular, see Michalik (2019).

single points on the retina. He does all this, Kepler says, without having performed or attended a dissection of the eye (Kepler 2000, 171).

Note the order of investigation: whereas Peckham and the other perspectivists offer the manner of vision first followed by the anatomy of the eye, Kepler places the anatomy of the eye prior to his determination of the manner of vision. He therefore derives his projection of a picture onto the retina in part from empirical investigations of the eye. He took his empirical account of the eye from anatomists and from them also drew his order of investigation—in particular, from Fabricius ab Aquapendente, via the latter's student Johannes Jessenius (Baker 2019, 141–42). This new order, in which the anatomy of the eye precedes and helps determine the manner of vision, was also followed by later writers, including Scheiner, Descartes, and the Jesuit mathematician and polymath François d'Aguilon (1613, 2–12).

Even contemporaries with the mathematical aptitude to understand Kepler's results might be skeptical of certain steps in his larger investigation. In his 1637 *Dioptrique*, on the other hand, Descartes takes a different approach. Like Kepler, Descartes begins with a treatise on light and argues that light and color are mechanical—a combined tendency of linear and rotational motion of the tiny globules comprising the second kind of matter in Descartes's physical world.[13] He next demonstrates the sine rule of refraction in discourse two; gives an abbreviated anatomy of the eye in discourse three; posits, in discourse four, an account of the senses in general, in which he discards the scholastic view on natural images; and then argues for the retinal theory of vision in discourse five. He accomplishes the last goal, however, by pointing to a simple experiment that allows one to see the inverted picture of the world cast on the retina: "if, taking the eye of a newly deceased man, or for lack of this, that of ox or some other large animal, you skillfully cut through the three coats that enclose it at the base…" (1637, 35). Here Descartes does not give a mathematical demonstration of the path of rays through the eye, but merely refers to the experience of seeing an inverted image on the back of a dissected eye. With this qualitative account of how the rays ought to refract within the eye, he then trusts that his reader will either perform the experiment or else assent to the scheme depicted in his famous diagram.

Notably, Scheiner himself made the same argument in his 1626 *Rosa ursina,* though he presented it as a witnessed experience rather than performance instructions. He also omitted a diagram, which was crucial for Descartes. Scheiner (1626, 110) writes:

> For the rest, that the crossing of rays is made before the image of the object is formed on the Retina yz was not only demonstrated by many exceedingly evident experiments and reasonings in my *Oculus*, but also in a human eye seen publicly here in Rome in the Jubilee Year [1625], where having removed the sclera from the base of the eye, the light of a candle sent through the pupil fell upon the Retinal tunic with crossed rays: which I have also shown to

[13] For Descartes's account of light and color, and the experimental basis for his description of the rainbow, see Buchwald (2008).

> be true in the eyes of many brute animals. This anatomy of the eye was made by the Reverend Father Niccolò Zucchi in my presence, performed as a favor to me.[14]

Zucchi (1586–1670) was a Jesuit philosopher, astronomer, and mathematician. The experiment he helped perform likely occurred years before similar ones by Descartes. As Scheiner says, however, in 1619 he had recourse only to reasoning from more indirect, though "exceedingly evident," experiments.

Descartes was able to argue for the *camera obscura* model of vision rather easily, and did so in a work aimed at a more general audience, in part because the retinal theory was already making significant inroads. But, for the most part, this was not because Descartes's readers had wrestled with Kepler's difficult *Paralipomena*. Scheiner likely deserves a good deal of credit for converting people to the retinal theory, particularly given the pedagogical reach of the Jesuits. So too does Descartes's one-time collaborator and later critic, the physician Vopiscus Fortunatus Plempius, who advocated for an Aristotelized retinal theory in his medico-philosophical *Ophthalmographia* (1632, 172–74).

2.5 Scheiner on the Eye as the Foundation of Optics

Scheiner divides the *Oculus* into three books. Book I has two parts, the first containing an in-depth anatomy of the eye, although he says that he omits details relating to medicine and the functioning of the eye in general that do not pertain to the foundations of a mathematical theory of vision. In the second part of book I he writes,

> In the second part we report experiences (*experientiae*) as needed in these matters, so that from them we might establish the truth, and refute errors. Indeed, one true experience, as the Philosopher attests, is worth more than a thousand deceitful strings of sly reasoning.[15] (1)

In his preface describing book II he writes, "we examine the visual ray *formaliter*, first from the nature of refraction in general, then with respect to that which concerns the eye in particular" (*ii). By "formaliter" Scheiner means that the path of rays is treated without an account of the physical causes of refraction. Finally, in the preface he also describes the aim of book III: "The retinal tunic is established as the organ of vision, the visual angle is described in detail, and various objections, difficulties and curious questions are examined" (*iii).

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[14] "Caeterum decussationem radiorum fieri antequam imago objecti in Retina yz effigietur, non tantum in Oculo meo multis evidentissimis experimentis atque rationibus demonstravi, sed etiam in oculo humano hic Rome anno Iubilaeo apertissimè vidi, ubi abrasi in fundo oculi sclerode, immissum candelae per pupillam lumen radiis decussatis in tunicam Retinam accidit: id quod in multis brutorum oculis saepius expertus eram. Facta est autem haec Oculi Anatome à in praesentia R. P. Nicolae Zucchi, in gratiam meam instituta."

[15] "Parte secunda experientias pro re nata adferimus: ut ex illis veritatem stabiliamus, refellamus errores. Una enim vera experientia, Philosopho teste, plus valet, quam mille rationum subtolarum fallaces argutiae."

The first part of book I, as mentioned, is a detailed anatomy of the eye, along with a new diagram or image of the eye containing significant innovations compared to previous diagrams (Raynaud 2020, 108). This material also includes an account of the physical causes of the construction of the eye, and a description of how to dissect it. As to the necessity of this first anatomical section—consisting of about twenty-eight pages—Scheiner says:

> The preconditions for beginning our work are not so much the Phenomena, but rather experiments drawn out with singular zeal, which are of two kinds: the one from the inspection of the eye; the other from the species of things perceived in the eye under certain conditions.[16] (Scheiner 1619, 1)

What Scheiner means by "phenomena" will be discussed later. He lists several reasons for the necessity of ocular anatomy: to determine both whether substances are continuous or distinct, which is necessary to identify places where rays refract; and to determine the degrees of transparency and opacity of the parts, their shapes, the density or rarity of the parts and the differences between them, the magnitude of the parts, and where they are located. All these factors affect the path of rays in the eye, and the foundation of optics just is the determination of the path of rays in the eye. The purpose of doing anatomy, therefore, is both to refute mistaken assumptions that earlier authors had relied on, and to establish a true natural-philosophical account of the act of seeing, from which basis mathematical propositions related to vision can be demonstrated. Scheiner, in fact, cites Fabricius's remarks in *De visione,* part 3 chapter 8, where the latter writes that a true anatomy of the eye should be used to establish the progression of rays through it, the angles of their refraction through the parts, and so on (ab Aquapendente 1600, 105). Note, however, that Scheiner says he came upon this passage only after he had begun his own anatomical investigations (Scheiner 1619, 20).

We might find it curious that Scheiner does not proceed by developing or drawing from the mathematical science of dioptrics first, in order to use those results to understand the path of visual rays in the eye and thus the manner of vision. From the middle of the seventeenth century we increasingly see this order, relegating the formation of images on the retina to a special case of the science of optics (understood as the mathematics of the reflection and refraction of light). For his part, Scheiner still conceives of optics as a middle science, a discipline that combines the principles of physics—particularly the science of the soul, which encompasses perception—with those of mathematics. His treatment of the eye and visual experience is an attempt to establish those areas of physics (including physiology and psychology) that will be relied on to generate the postulates or axioms of optics, and also to tell us what we need to do to establish and secure those parts of physics. The

[16] "Praecognita ad institutum nostrum non tam sunt Phaenomena, quam experimenta singulari studio hausta, eaque duplicis generis; altera ex oculi inspectione; atlera e specierum a rebus aspectabilibus in oculum diffusarum consideratione desumpta." Dear renders the first sentence, "singular experiments derived from study," and while I find, with Dear, that Scheiner makes a distinction between "singular experiments" and general (and more universal) experiences, I don't quite see this distinction highlighted here.

geometrical foundations for optics, on the other hand, were relatively better established, although he does review some of this material in his treatise.

Scheiner's uses experiments with particular dissections of the eye to build a universal account of the human organ of vision. In this method Scheiner was inspired by the anatomical tradition—particularly out of Padua—which was, as we have seen, built on a synthesis of Aristotelian and Galenic approaches. The methodological norms related to control in contemporaneous anatomical treatises are largely implicit, but by teasing them out via a comparison of many such treatises (and by relying on some explicit statements, particularly from Paduan anatomists), we find that particular experiments or dissections ought to be repeated. The visual and tactile sensations given in those dissections were then to be compared with the writings (and perhaps visual depictions) of relevant authorities, until the investigator arrived at a state of secure understanding for the fabric of the universal part. Moreover, after Vesalius, images were increasingly important for anatomical knowledge, and one important result of Scheiner's anatomy is what he calls an *effigies*—an image or diagram—of the eye (see Fig. 2.3).

Scheiner makes several important corrections to prevailing ocular anatomies. The most obvious one, and that most noted by historians, is that the optic nerve enters the bulb nasally. All previous anatomists and perspectivists thought that it was in a direct line with the visual axis (D in Fig. 2.3), and this change impacts Scheiner's account of vision. He also argues that the corneal bulge, only recently noted by anatomists, is not spherical as commonly described, but either a parabolic or hyperbolic spheroid (8); in this he was almost certainly taking inspiration from Kepler's discussions of conic sections in the *Paralipomena* (Kepler 2000, 106–23, 183–87). Scheiner's crystalline humor (G) is somewhat more forward than most

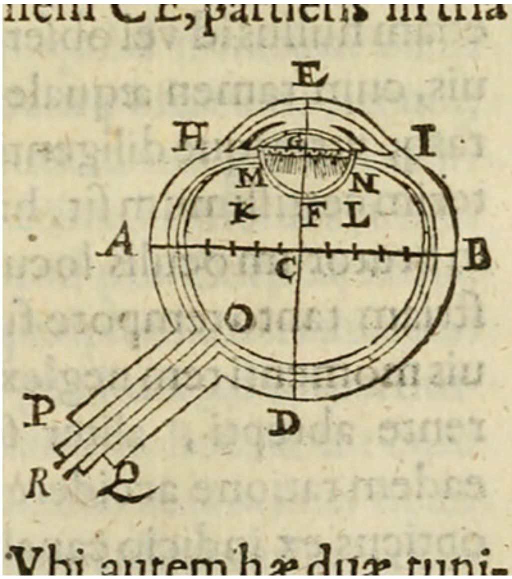

Fig. 2.3 An effigies or diagram of the eye (Scheiner 1619, 17)

anatomists placed it as well. He says that both sides of the crystalline humor are portions of a sphere, the rear having a small radius, and thus more curvature, than the front (9); this contradicts Kepler's claim that the rear is a hyperbolic conoid (Kepler 2000, 179).[17] Despite adopting the retinal theory from Kepler, Scheiner's dissections led him to a more traditional description of the surfaces of the crystalline lens.

It should be noted that Scheiner first gives the names and a general description of the parts, then in a subsequent chapter enumerates the parts according to transparency and opacity. He then describes, in a geometric fashion, the eye's tunics, then its humors, and lastly explicates at length his image or diagram of the eye, which is in a sense a synthesis of the previous chapters.

Concerning his remarks on dissection procedure and on how he arrived at his anatomical account of the eye, he says that he leaves a more thorough investigation to the physicians (*medici*) and physicists (*physici*), and that "it is sufficient for us to investigate the number, size, shape, position, transparency, density, and similar characteristics of the parts of the eye" (25). This investigation would require an extremely sharp knife and several long needles to probe and secure the parts as needed. He also writes, "it is better to examine and pursue a single aspect of the eye with precision and certainty, rather than attempting to grasp everything all at once" (25). This goal implies a number of dissections and thus multiple eyes; it also contrasts with accounts in anatomical treatises of how to dissect eyes in public anatomies. Although human eyes are preferred, any animal eye will suffice, as Scheiner says that "the visual organ in the human eye is of the same kind (*species*) as that found in a bull or a horse" (26–27). Here he cites Fabricius's dissections of many different animals, made in order to understand the nature of vision generally. One can dissect either fresh (*crudus*) eyes or ones that have been tightened up (*constipatus*) somewhat in warm water. Each will reveal something different, although boiling the eye will ruin the anatomy. Likewise, eyes of the immediately deceased reveal different things compared to eyes that have dried out somewhat. For investigating the humors, only fresh eyes will do, and Scheiner gives instructions for how to empty the various chambers in order to measure the quantities of the humors. Finally, one should dissect in multiple ways, e.g., cutting transverse to the axis of vision, removing the tunics from the rear, from the front, and so on. In short, Scheiner's instructions are more detailed, and directed to more specific ends, than almost all contemporary accounts of ocular dissection.

All this fits easily into the well-trod epistemic path—roughly Aristotelian with Galenic influences—of gathering sensory experiences, storing them in memory, comparing them with the reports of others, and repeating until one *is experienced*, and from this is able to grasp the universals that are the starting points for the science in question. But Scheiner does not discuss just how much experience one needs to either securely arrive at universal knowledge of the relevant anatomical parts or how to resolve disagreements. He says merely that experience with many

[17] On the crystalline humor as a hyperbolic conoid, see Baker (2023, 138–40).

eyes is needed. He also says little about the problem of anatomical difference and individual variation. Moreover, he says that knowledge of the fabric of the eye will not alone reveal the nature of vision.

Scheiner goes beyond his predecessors in anatomy and optics in his meticulous measurements of the magnitude of the parts of the eye. While he does mention the problem of diversity and the difficulty of establishing precise accounts for the relative magnitudes of the parts, he concludes that if one measures a certain proportional magnitude in most cases, then the figures can be "firmly established" (12). His method for determining the curvatures of the various parts of the eye also involves careful and novel experimentation, though we will not cover that here.

In the second part of book I, Scheiner begins to use experiments to extend and develop the Aristotelian epistemic framework for grasping the first principles of a science: "Book I part 2, in 14 chapters, brings forth wonderful yet well-tested experiences on behalf of the teachings immediately following" (unnumbered index).[18] As Dear has observed, Scheiner makes a deliberate distinction between experiences (*experientiae)* and experiments (*experimenta*). Singular experiments lead to a general state of *having experiences* or *being experienced*. The *experimenta* are best understood in the context of *Posterior Analytics* II.19: sensations lead to memories, a sufficient collection of which result in experience. Again, we might say the experiments are events or singular sensations, while experience is something like a cognitive state. Experience without understanding is thus similar to the condition of an apprentice house-builder who knows how to do everything involved in house-building but does not yet know the *why* of it all.[19] An experienced person can therefore know or act in situations exactly like the particular ones they have experience with, but their efforts fail in new circumstances.

In the Middle Ages this issue was often discussed in the context of the problem of universals, thereby tying it to metaphysical questions—for instance, what is the ontological status of universals such that a series of particular experiences can cause universal knowledge to arise in the mind or soul? But Scheiner is not concerned with metaphysics and offers instead methodological and other practical solutions connected to the move from experience to understanding—imitating, it seems, Aristotle's approach to the problem in his treatises on individual sciences. Experiment, for Scheiner, thus becomes a way to further develop and refine one's cognitive state of having experience or being experienced, a refinement necessary to establish true first principles for a science.

To understand his methodology we can take the first two *experimenta*. His *experientia prima* concerns variations in the pupil, and he offers two *experimenta* to build one's experience of pupil variation. In the first, which is not new to him, he implores the reader to have someone look at a bright light and note how their pupil contracts; if this person looks away from this light, their pupil will dilate. In the

[18] "Liber 1, pars altera, miras sed exploratas pro subsequenti doctrina experientias capitibus 14 depromit."

[19] See 981a13–981b9.

second *experimentum* he asks the reader to look at a needle held at varying distances from the eye, while another person examines their pupil and notes its changes. Hold the needle a finger's breadth from the eye and then move it closer, and the pupil will contract; move away once again and it will dilate. From this result, "a sensible difference will be seen by he, whom you employ as a witness to truth and friend of philosophy" (30–31).[20] He mentions that no change in illumination is necessary to cause this dilation and contraction. After this narrative description of the procedure, he gives a more formal mathematical description, now written in the third person and illustrated with a diagram: "Let there be an eye, ABC, pupil AB, which is aiming toward a remote grain D. If the grain approaches towards point E…", and so on (see Fig. 2.4).

Observations about pupil dilation were used to support and attack theories of vision since Galen at least, but Scheiner's explicit structuring—listing several particular experiments that are supposed to lead one to a more general experience of how the pupil dilates—is perhaps new. His observation that the pupil contracts

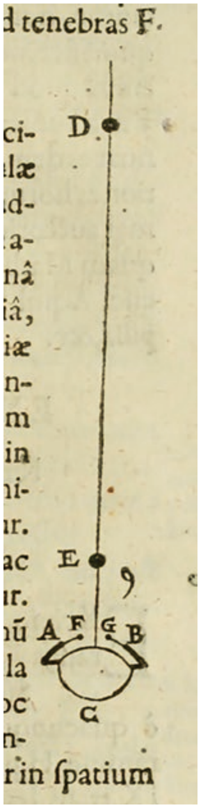

Fig. 2.4 Experience 1, experiment 2: a friend observes your pupil as a needle moves closer to and further away from your eye (Scheiner 1619, 31)

[20] "Ita ut crassitie digiti vix absit; una cum accessua aciculae ad oculum tuum claudetur pupilla eiusdem, una cum recessa ab eodem aperitur, sensibili differentiae quod videbit is, quem veritatis testem & philosophiae amicum adhibueris."

when close objects are moved closer appears to be novel as well. Scheiner here is building a curated stock of recorded experiences—starting with the easiest to gather—that he will later draw from to establish his first principles of optics.

While different, his arguments from pupil dilation were not unprecedented; Scheiner's second *experientia*, however, appears to be entirely new. He titles it "Things Seen through a Small Hole by Means of Crossed Rays" (32). Scheiner gives a sequence of contrived experiences that he directs his readers to have, but here he does not list a number of *experimenta* that build up to a generalized (though still narrow) *experientia*. This is because these experiences involve mere attention to one's direct, first-person perceptions under special conditions; indeed, he refers to the reader in the second person, imploring them to perform these *experimenta* and gather this body of *experientia* directly. This analysis supports the idea that he sees experience as an internal state, although one which can be shared by many people. "Experience" here is therefore best understood in the psychological sense from Aristotle's *Posterior Analytics*, rather than in the sense of evidence or shared public facts in the legal sense, as described by Barbara Shapiro (Shapiro 2000). Scheiner's contrived experiences are, we might say, private facts that are capable of being described and enumerated, and thus unproblematically referred to in demonstrations.

Scheiner directs his readers to take a *lamina* or thin sheet of opaque material (metal foil works well), which he designates DEFG, and which has a hole H. He says to peer through it to some object, which he labels IK (see Fig. 2.5). If another small opaque plate NO is placed between our eye and DEFG, and slowly moved leftwards across the hole from the right, we notice that our view of the body IK is obscured in the reverse direction—that is, we perceive point I disappearing before

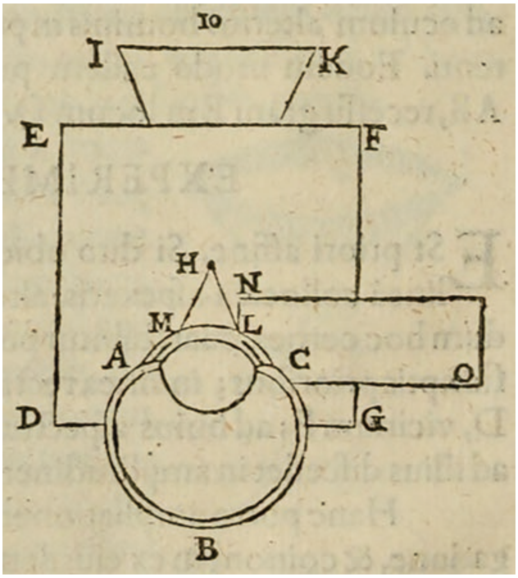

Fig. 2.5 Observing IK through a small aperture as the aperture is gradually blocked by plate NO (Scheiner 1619, 31)

point K, and indeed before the hole itself is obscured (Scheiner 1619, 32). Placing the small plate NO behind the sheet DEFG, and once again moving it across the hole from right to left, we notice that this time point K is obscured before point I. Scheiner's marginal index for this section reads, "Decussatio radiorum demonstratur," or "Crossing of the rays is demonstrated" (32). He lists, moreover, seven *proprietates* or special characteristics arising from this illuminating experience (*lucentia experienta)*. In addition to conclusions about the crossing of rays, these results include all sorts of things seen and deduced from the experience: if the hole is too big the rays do not cross; when the hole is small the things seen through it appear to be smaller, but are apprehended more precisely, distinctly, and accurately; if we move the small hole away from our eye, the thing seen through the hole appears smaller and becomes more indistinct; and so on.

There are eleven *experientiae* in book I part II. Experience five is titled, "With one eye it is possible to see, distinctly, the same thing two, three, or four times, without employing any additional diaphanous [body]" (37). Here Scheiner has the reader look through a thin plate with two, three, or four holes spaced "smaller than the width of your pupil" (see Fig. 2.6). Closing one eye, if you look through it at stars or other small bright objects at night, you will see them doubled, tripled, or quadrupled, depending on the number of holes. Note, however, that only individuals with ametropia will see the images variously doubled, tripled, etc. Thus, this contrived experience is not universal, contrary to what Scheiner thought.

Experience six shows the reader how to experience the reverse: "Not only can one thing appear multiple, in the way mentioned above, but [it] also may appear as

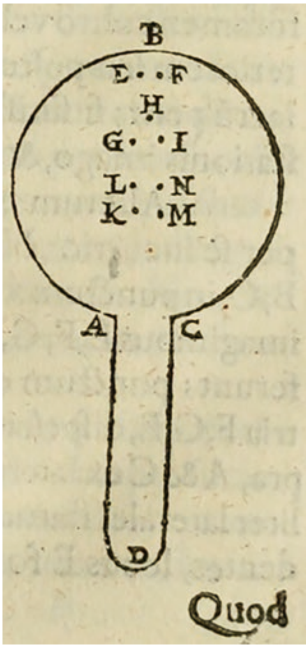

Fig. 2.6 "Take a round, thin plate (metal is best) with a handle ADC. Pierce holes E & F as shown, smaller than the width of your pupil. Close your other eye, and place it very close to your eye" (Scheiner 1619, 36–37)

one thing via many apertures" (41). After each of these chapters Scheiner appends another in which he discusses how to perform them properly, what other kinds of phenomena (such as color change seen through the apertures) arise, and so on. At various points he insists that the reader directly experience all the phenomena that will later be used to establish the foundations of optics in books II and III.

Two of the eleven experiences describe individuals with vision defects. Experience four is a report of a man with a peculiar cataract; Scheiner labels this chapter, "The crossing of visible rays into the eye is evident, as nature herself shows."

> There is a man, still among the living, whose left eye is covered with a kind of innate white little cloud, such that access to the pupil is not open to species except for a small space much like the sharp crescent of the new moon… .[21] (36)

If an object (see Fig. 2.7) ILNK is in front of such a person, points I, L, and N will not be seen, but K, via ray HK, will be seen. (K is to the bottom right, but somewhat illegible here owing to a poor impression in the copy I examined.) Again, Scheiner's conclusion here is that "this experience (*experientia*) establishes that things are gazed upon (*aspicere*) through crosswise rays" (36–7). Experience eight likewise discusses general experiences of those with partial *suffusiones* or cataracts, including a notable report copied at length from a text of the physician Ioannes Theodorus. Scheiner thus appeals to direct, first-person contrived experiences, as well as to reliable narratives of the experiences of others in situations where nature seems to act outside of its normal course.

So in addition to (1) first-hand anatomical knowledge, in this first book Scheiner refers to (2) individual experiments, (3) specific, detailed, and contrived first-person experiences, (4) individual, credible narrative reports about extraordinary visual defects, and (5) conclusions derived from general experience in other domains, such as medicine. All methods, for Scheiner, are perfectly valid for developing the broad but well-ordered experience concerning anatomy, physiology, and visual phenomena required to put optics on a secure foundation.

What does Scheiner do with these experiments and experiences? At the end of book I, he writes:

> In the course of this work you will frequently land upon other experiences not touched upon here, which you will also sufficiently elucidate, as I trust, by your worthy reckoning, and you will add many discovered by other performers or by your own *ingenium* or experiments, to which, as if by repeated blows, you will impress the nail of this opinion and doctrine upon your own minds and upon the minds of others, so that you will never undergo any foreign persuasion to tear you from it.[22] (52)

[21] "Est homo, etiamnum in vivis, cuius sinsitra oculi pupilla obducta est alba quadam sed nativa nubccula [sic], ut vel in eandem, vel ex eadem pupilla aditus non pateat speciebus nisi spatio tantillo quantum novae lunae falx acutissimo visui largiri dignatur…"

[22] "In alias experientias hic ex instituto non tactas incides frequenter huius totius operis decursus, quas etiam satis elucidatas, uti confiso, calculo tuo approbis, multasque ab aliis actoribus, aut ingenio aut experimento proprio inventas adiunges, quibus velut ictibus repetitis sententiae atque doctrinae huiusce clavum ita tua aliorumque mentibus infinges, ut ab ea. te divelli nulla aliena persuasione ullatenus patiaris."

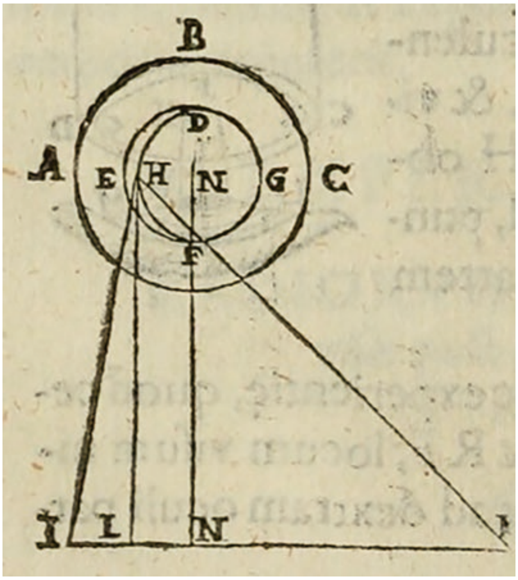

Fig. 2.7 An account of a man with a cataract covering all but the crescent-shaped area DEFH, with the object ILNK in the visual field (Scheiner 1619, 36–37)

This passage calls to mind Aristotle's *Posterior Analytics* II.19, in which *nous*, or knowledge of first principles which is arrived at via experience, is even more secure than *episteme* or demonstrative knowledge. What in later methodological frameworks might loosely be called "perceptual" experiments are, for Scheiner, pathways for acquiring experience. These experiences are not universal knowledge *per se*, but they are nevertheless more general than any particular experiment, at least in the sense that they do not consist of a single, particular memory but an organized collection of them. A sufficient collection of such experiences allows one to grasp the universal first principles of a science via the process of induction. But again, note that in the quote above Scheiner is not appealing to the psychological state of having experience in order to justify the truth or validity of his first principles. Instead, as we will see, he is building toward a forceful persuasion via argumentation from meticulously curated experience and experiment. However mysterious, according to some modern commentators, this move (discussed both at the end of the *Posterior Analytics* and in *De anima* book III, chapters 4 and 5) from particulars to universals might seem, Scheiner's use of his carefully curated stock of experiences to establish the beginnings of the science of optics is hardly so. He is simply instructing his readers how to gather certain requisite experiences and then drawing out certain conclusions.

Thus, Scheiner begins in book II by eliminating various parts of the eye as contenders for the seat of the visual faculty, arguing that they are incompatible with the results of the experiments and experiences he recorded in the previous book. To do so he cites his list of experiences by number and section. For instance, on the opinion that the cornea is the seat of visual sensation, he writes that this is not possible "because experiences 4, 8, and 9 part 2, chapters 4, 11, and 12, and also 13 and 14, are all alike inconsistent with this opinion" (57). The fact that these experiments and contrived experiences are systematically written down is key—Scheiner is engaged, one might say, in a project of making experience literate.[23] Along the way, in book II, he introduces a number of points about the refraction of light, the relative refractive powers of the various humors (here appealing to both his own anatomical experiments as well as those of others), the nature of rays (or species) of light and color, and so on.

In book III, part 1 he concludes that the retina is the seat of vision, both by process of elimination and owing to the fact that the substance and position of the retina are appropriate for receiving visible rays. In book III, part 2 he reconstructs the visual cone using the retinal theory, thus allowing that theory to accommodate Euclid's axioms. The expanded set of principles found in the later perspectivists, such as Alhazen and Peckham, are not necessarily retained. The crucial benefit of the retinal theory of vision is that, unlike the traditional visual cone model, it combines seamlessly with the burgeoning science of dioptrics—the science for understanding the effects of burning lenses, eyeglasses, and telescopes—particularly as developed by Kepler (1611; Malet 2003). A good portion of book III, part 2 is therefore spent resolving outstanding questions about experiences with eyeglasses, telescopes, vision disorders, and other matters.

2.6 Conclusion

We return to Peter Dear, who asked, "How could 'experience' be established as common property if most people lacked direct access to them?" (1987, 160.) A few pages later he elaborates:

> experimental knowledge was recondite, constituting private rather than public experience, and if it failed to achieve public warrant it could not form part of a science. In order to legitimate experimental statements, therefore, the mathematician had to find ways of extending private experience to his audience through the medium of the mathematical treatise itself. (167)

Finally:

> much of the experiential basis of astronomy and of optics was manufactured by expert practitioners, and could not easily be transformed into the evident experience which would provide adequate principles for a true science. (174)

[23] Although Scheiner's work predates Francis Bacon's *Insauratio magna*, I allude to the notion of *experientia literata* found in the latter*:* "A two-sided activity, *experientia literata* was at the same time concerned with the production of experiments and their presentation in structured, systematic accounts. However, experimentation reached its "literate" stage only if detailed in written reports" (Pastorino 2011, 543). See also Jalobeanu (2016); in addition to Scheiner's carefully written reports, one can arguably find within Scheiner's *Oculus* many of the "patterns of inquiry" that Jalobeanu identifies in Bacon.

I argue that there are several reasons why Dear's suggested obstacles were, for Scheiner, not radical epistemic problems. The first is that Dear, and many other twentieth-century historians and philosophers of science, took Aristotle's *Posterior Analytics* as providing an epistemic justification for grasping first principles. On this account, for an Aristotelian to justify their indemonstrable starting points for a science, they could only appeal to commonly accepted experiences that are the basis for the inductive leap to universal first principles. Against this view, I argue that early modern Aristotelians read the *Posterior Analytics* more in line with the recent scholarly account sketched above. Because the justification of one's axioms or starting points is different for each science, the steps for gathering experience and comprehending the first principles of a science from this experience look different for each science. Such accounts, far more nuanced and elaborate than that given in the *Posterior Analytics*, were given at the beginning of each treatise on that particular science. Indeed Scheiner's *Oculus, hoc est fundamentum opticum* is a treatise on exactly that: the foundations or principles of optics. That is, experiences need not be "common" in the sense that anyone whatsoever would assent to them as a matter of "common sense" (or whatever vague notion of shared experience was thrust on premodern and early modern Aristotelians). Rather, these experiences can be generated in a reader. The author may offer clear directions for contrived experiences and experiments in order to ask that the reader build the experiences up themselves. The author may then ask that the reader accept the reports of reputable observers, like physicians, about both nature in its normal course as well as nature outside its normal course in specific instances. This request would hold provided that the deviations from the norm reveal *different aspects of the normal course of nature*. This last way of generating experience is shown with Scheiner's use of the man with an unusual cataract. The cataract itself is extraordinary, but the small portion of rays that do enter his eye behave as normal, which (he argues) reveals something about the normal action of the eye in refracting incoming rays.

In short, nothing about Aristotelianism prevents these experiences from being complex, from interacting in complicated ways, or from requiring argumentation—or at least ordering—for their consequences to be felt. Furthermore, I argue that Scheiner's work shows that the early modern project of developing methods and techniques for properly establishing first principles or axioms was general—it was not confined to *novatores* such as Bacon or Galileo.

Another issue is that Dear and others take optics to be the science of light, rather than the science of sight. As a result, many authors fail to see the crucial influence of the Galeno–Aristotelian anatomical tradition on optics. This tradition used contrived experiences and experiments and tried to understand final causes and occult "natures" and/or faculties via the dissection of dead bodies (i.e., bodies necessarily *lacking* those natures or faculties). Few in the early modern period doubted the epistemic validity of anatomy, which at the time included what we would call physiology. Thus, to the extent that Scheiner incorporated a similar approach, he was on firm footing. Furthermore, given that the science of optics drew its principles from the physics of the soul, and not merely from the physics of light rays, first-person experience was an ideal starting point for such an investigation.

Again, Scheiner says that he starts not so much from phenomena but from experiments. By "phenomena" he means the standard list of generally accepted visual experiences: that bodies of the same size appear smaller when further away, that square towers in the distance appear round, that objects in flat mirrors appear reversed, and so on. All these phenomena are adequately dealt with via the traditional visual cone, and thus by reconstructing the visual cone within the new retinal theory, Scheiner does not need to worry about addressing the phenomena when starting his inquiry. Scheiner is concerned with sight, understood philosophically (and thus anatomically, physiologically, and psychologically), primarily as it pertains to optics. He wishes to update the physical principles taken for granted at the beginning of a mathematical treatise on optics, an update that became necessary owing to the cracks in perspectivist optics revealed by the works of Paduan anatomists (Fabricius in particular), by Kepler's *Paralipomena,* and by the telescope.

The experimental knowledge that Scheiner directs his readers to obtain is not exactly recondite. I performed most of his experiences successfully, in a few hours, with a few pieces of aluminum foil and a needle. I also found myself largely assenting to his descriptions of these experiences. Such experience is certainly private, but this is precisely what is required to establish the first principles of a mathematical science building on the science of the soul—a science that included the science of sensation and of the sensibles. Private experiences were what the discipline of optics in the second decade of the seventeenth century demanded: they were necessary, but not sufficient. Anatomical knowledge, investigations of light, geometrical knowledge, and other things were also required; moreover, any such contrived experiences and experiments must be repeatable by others. Scheiner does indeed generalize and extend these experiences by means of mathematics—and Dear's description here is correct—but in this there is nothing radically new or strange from the point of view of Aristotelian epistemology or natural philosophy.

Scheiner's *Oculus* belongs only partly to the history of mathematical optics in the modern sense of the science of light and image formation. It belongs more obviously to the long history of perception, as studied by both philosophers and historians of science. This history reaches to Plato and Aristotle, embraces Euclid and Ptolemy, and traces through medieval perspectivists and scholastic philosophers. Moving forward from Scheiner, this history should be seen as eventually feeding into nineteenth-century physiological optics, which was concerned at once with the anatomy and physiology of the visual system together and with issues such as distance, size, and color perception. Helmholtz, for instance, cites Scheiner many times in his 1866 *Handbook of Physiological Optics* (Von Helmholtz 1867).

The larger issue of rigor and control in sciences attempting to understand and explain first-person experiences is worth considering. Scheiner leaned on an Aristotelian psychological model of knowledge, while also drawing from developments in anatomy. Within the latter, final causes helped to structure investigations and offered ways to argue for or against various theories. Appeals to final causes lost epistemic validity as the seventeenth century went on, however, and thus Scheiner's arguments likely lost some of their force over time. We should also note that Scheiner assumes the results of his first-person contrived experiences could be unproblematically generalized. Obviously not all of them can be. For this reason, what has come to be called "Scheiner's experiment" (see Fig. 2.6) is now a test for the visual defect of ametropia: if one looks through a plate or card having two small holes, very closely spaced, with the card placed very close to the eye, that person will see one thing as doubled only if they have a refractive error in their vision whereby distant points do not focus properly on the retina. Scheiner apparently had ametropia. So do I, and when I performed his simple experiment I confirmed what he saw. Thus, Scheiner does not have an explicit method to control for such issues or to resolve them should a controversy arise owing to differences in self-reports. While issues with self-reported perceptual experiments were known and debated in the nineteenth century, what the interim period looks like has not been much explored.

In what way, then, has Scheiner engaged with control practices in the sense relevant to this volume? In attempting to put optics (as the science of sight) on a firm experimental and experiential foundation, Scheiner used experiment and contrived experiences to lay out the possible sites of visual sensitivity in the eye. He then eliminated all but one, often using multiple kinds of evidence; someone gathering the experiences Scheiner sets forth should have no choice but to accept the axioms of optics he presents at the end. However, his experiments and contrived experiences could have been organized differently, from our perspective—for example, in a hypothetico-deductive fashion (Coko, Chap. 8, this volume). While preserving his foundation of rigor and exact anatomy, it would not be hard to rewrite the treatise so that each hypothesis about the manner and seat of vision in the eye would be first presented and then refuted one at a time by using the same experiments he gathered in the second part of book I. In the end, only the retinal hypothesis would remain.

In the *Oculus*, Scheiner does not seem to employ multiple determination in quite the way described by Christopoulou and Arabatzis (Chap. 9, this volume). A sort of second independent determination of the site of sensitivity, however, seems to be used later in Scheiner's *Rosa ursina*. As mentioned above, there he performs the dissection experiment made famous by Descartes 11 years later: the sclera and *uvea* (or choroid tunic) at the back of an eye are removed and the eye is seen to act like a miniature *camera obscura*, with an inverted picture of the world projected on the retina. (In my experience, getting a clear image to appear in this way is not at all straightforward. It is no surprise this was the last method used to establish the retinal theory.) Finally, Kepler's mathematical approach gives us a third independent determination of the site of sensitivity in the eye. He combines a geometrical account of the refraction of rays passing through a sphere with the solution to the problem of pinhole images. To this he adds additional clever mathematical approximations and analogies and then, based on recent anatomical knowledge of the eye, attempts to persuade the reader that the eye casts a picture of the world on the retina. We might label these separate determinations of the *camera obscura* model of the eye the experiential-mathematical-eliminative (Scheiner's *Oculus*), the direct observational (Descartes, Scheiner's *Rosa ursina*), and the mathematical-analogical (Kepler) determinations.

We can also note that, because the private visual experiences of humans can be communicated, challenges to control here seem to be distinct from those involving experiments on non-human animals (Hoffmann, Chap. 11, this volume) and plants (Nickelsen, Chap. 7, this volume; Schürch, Chap. 3, this volume), where only reactions to stimuli can be observed.

The issues of how many experiments are necessary, of replication, and of including parallel trials do not operate in the same way here compared with experiments establishing public facts. For most of Scheiner's self-experiments, one must simply work until one is able to consistently achieve the (private) perceptual experience. Convincing others of the effect demands that they perform the experiment and achieve the experience directly, which again is generally easy to do. The medical reports Scheiner deploys were also apparently understood as reliable and unproblematic, although in any case they are supplementary, something like confirming evidence. It does seem that Scheiner uses something similar to the Baconian strategy of varying the parameters that Coko (Chap. 8, this volume) describes, although certainly in a less sophisticated manner than Coko's actors.

Arguably, any scientific methodology involves control strategies. It seems that premodern and early-modern Aristotelians, however, might easily have been omitted from a history of control. The received account is that experimentation, and therefore the control strategies needed for experimental rigor, developed only in spite of or in opposition to Aristotelian methodological/epistemological precepts. However, Aristotelianism shaped the strategies in Scheiner's *Oculus*, and if anything, his Aristotelianism offered (by the standards of the time) more solutions to experimental issues than it did obstacles. I suggest, but cannot fully argue here, that the decline of Aristotelianism in the seventeenth century was thus not primarily attributable to a fundamental weakness in its methodology or epistemology. To the degree that control strategies are responses to criticism both internal and external to certain disciplines, it seems that one major reason why these strategies were increasingly discussed in the early modern period was the sheer amount of experimental activity and the concomitant explosion in argumentation and criticism. This was a rising tide that lifted all boats.

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