Chapter 7
Exploring the Challenges and Opportunities of Theory-Laden Observation and Subjectivity: A Key NOS Notion

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7.1 Introduction

A major aspect of the nature of science (NOS) that should be communicated to students is the idea that scientists—and everyone else for that matter—have prior notions about what they will ultimately "see" when looking at phenomena, and that these prior ideas interact with the act of observation itself. This is not surprising; considering the range of sense data that flow in daily, it is quite useful for the mind to turn itself off—in a sense—when the data are not deemed useful. All of us engage in this form of unconscious selective observation. The situation is the same in classrooms. We tell students when looking through the microscope to "draw what you see," and then question when they have included so many air bubbles. Students learn quickly that these bubbles are not considered useful data and soon fail to include them in their drawings. We often talk about learning to observe as a vital part of school science laboratory work, but how many of us teach students about the limits of observation and the potentially confounding role of prior knowledge when making observations? These are extraordinarily important lessons that relate closely to the nature of science itself and the notion that observation-making is very tricky business.

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7.2 Observations, "Theories," and the Myth of Complete Subjectivity

Norris (1985) correctly stated that observation is fundamental in science but warns that it is a misconception to suggest that observation is "the simplest of all intellectual activities of scientists" (p. 817). To the contrary, the act of observing is far from something that is uncomplicated, automatic, or even trivial as some might believe. All observations are directed by advance notions of what is likely to be observed, although the observer typically does not appreciate the role played by this advance expectation. Observation, therefore, is an active rather than passive process (Hainsworth 1956) comprising at least three steps: a source [the observed object or phenomenon] that releases information, the transmission of data, and the reception of these data by the observer or instrument (Shapere 1982). This last point has become known as "theory-ladenness" "the view that observation cannot function in an unbiased way in the testing of theories because observational judgments are affected by the theoretical beliefs of the observer" (Franklin 2015, p. 155).

The transmission of useful data from object through observer may seem linear, but we would be wise to heed the warning of Alphonse Bertillon (1853–1914), one of the founders of forensic science, who said, "one can only see what one observes, and one observes only things that are already in the mind." What this means to scientists, science teachers, and science students is that prior knowledge both helps to direct and confound the act of observing. Although this is a vital element of the nature of scientific investigation, the pitfalls and potential of observation are rarely communicated to those engaged in the science learning enterprise. "Observations … mark the beginning points of reasoning in the area of knowledge in question, the basis upon which other knowledge rests" (Norris 1985, p. 824); observation is more complex than the simple act of looking at or measuring something. Rather, observation depends on inferential procedures (Duschl 1985; Norris 1985).

The prior inferences or conceptions held by observers are what Hanson (1958) called "theory-laden" and are formed by the intermingling of knowledge, background, and observation. Hanson (1958) states further that the "observation of χ is shaped by prior knowledge of χ" (p. 19). Gould (1994) discusses the issue of the complexity of observation and theory development by saying, "[S]cientists … tend to be unaware of their own mental impositions upon the world's messy and ambiguous factuality. Such mental impositions arise from a variety of sources, including psychological predisposition and social context" (p. 67). "When scientists adopt the myth that theories arise solely from observations, and do not grasp the personal and social influences acting on their thinking, they not only miss the causes of their changed opinions; they may even fail to comprehend the deep mental shift encoded by the new theory" (p. 68).

Before proceeding further, it would be wise to consider the different uses of the word "theory," found in the expressions "theory-laden" or "theory-based" observation and in the quotes from Gould. Hanson is using "theory" in the commonsense fashion where the term means an idea. So here we see that ones' prior ideas can dramatically alter the nature of the observations they make. Gould does not help much when he seems to refer to any scientific idea as a "theory," but he is correct that scientists and other observers often pay little attention to "the personal and social influences" (p. 67) that act upon thinking, but the results of the experiment presented later in this chapter clearly demonstrate that they should.

So, we can see that the label of "theory-laden" observation is problematic because of the potential for confusion that exists when considering the more precise definition of "theory" as ideas that explain why and how laws operate as they do. It would be far better to talk about *idea-based observations* or *prior concept-based observations*, but it would be foolish to expect that the "theory-laden" or "theory-based" label will be easily replaced. The literature is replete with references to this issue (Brewer and Lambert 2001) so we will maintain it here, but with quotes.

There has been continued interest among historians and philosophers of science on the issue of "theory." Brewer (2015) and Franklin (2015) have discussed the role of "theory" in the conduct of experiment and Schindler (2013) offered three related ideas about what theory-ladenness means in practice. He states that (1) observations are linked to some guiding idea or "theory," (2) that these guiding ideas help to make some observations more important or worthy than others, and (3) that our theories impact what we "see." In a comprehensive article replete with example, *Learning to See*, that strongly supports many of the themes expressed here the author tells us that "learning to see I not an innate gift; it is an iterative process, always in flux and constituted by the culture in which we find ourselves and the tools we have to hand" (Tracy 2018, p. 242).

Finally, this notion of "theory-based" observation provides an opportunity to discuss two related notions, that of "confirmation bias" and the closely related NOS notion, that of subjectivity in science. First a brief mention of the idea of confirmation bias which is the tendency to interpret new evidence as confirmation of ones' existing ideas or beliefs (Nickerson 1998). One side of the confirmation coin is almost inevitable. We somewhat naturally and even unconsciously pay more attention to information sources that are likely to speak to our deeply held views because we are more likely to value and respect such sources of information. The other perspective is that we actively look for and attend to information sources only that support and reinforce our world views probably to avoid being challenged. Even if we can forgive ourselves these natural inclinations, those who truly want to understand a phenomenon must work assiduously against only confirming what we think we already know. One proviso is that any source of information whether confirming or not must provide valid and reliable data and in the era of "fake news" in which this chapter was written, making that determination can be problematic.

The issue of subjectivity as a key NOS notion is discussed in some detail in Chap. 2 of this book, but a review here will be useful to link it with the challenges of observations. As we have established, scientists have their own advance notions about the potential meaning of any observation. Therefore, it is useful for students to understand that science itself possesses a more subjective character than they might have thought. This is certainly true when considering individual scientists and perhaps even laboratory working groups. As we will see in the sections that follow while there are some advantages to holding a prior view about the nature of evidence and the expectations of observations this can cause problems.

In the final analysis even though there is a subjective character to science, the scientific enterprise is populated by diverse people with a variety of views who operate within a collective check and balance system. So, while it is quite reasonable and accurate to admit that science has subjective elements—particularly as new observations and conclusions are initially being offered—the final judgment of science becomes increasingly objective as conclusions are vetted by and through the greater scientific establishment tempered by time and the further considerations of scientists in the future. The phrase the "truth will out" widely quoted from Shakespere's *Merchant of Venice* neatly summarizes and predicts the work of the scientific enterprise in addressing the challenges of scientific subjectivity.

7.3 Pros and Cons of "Theory-Based" Observations in Science

So, let us return to the issue that all of us—scientists included—make observations and interpret what we see based on our prior understanding and experiences. This reality "To the observing scientist, [theory] is both friend and enemy" (Boring 1950, p. 601). From a positive perspective, knowing what to look for and ignoring what is likely to be useless or distracting is useful. Beveridge (1957) was correct when he pointed out that "the prepared mind may make many more significant observations than the unprepared" (p. 46). Darwin (1850) who, when asked about his method of observation, stated that he speculated on any subject he encountered. He stated, "I can have no doubt that speculative men [sic], with a curb on, make far the best observers…" Mayr (1991) reflected on this by stating that speculating or theorizing (another dubious use of the term) is a "time-honored method of the best naturalists. They observe numerous phenomena and always try to understand the how and why of their observations. When something does not fall into place, they make a conjecture and test it by additional observation…" (pp. 9–10). Here it would seem that knowing what to look for, knowing in advance what is useful information, and then speculating on what it means is how the best scientists must all work.

As an example, consider the work of physicist Robert Millikan. He designed his famous oil drop experiments, to determine the charge on the electron. After his death, Millikan's laboratory notebooks—never intended to be published—became available for study (Franklin 1981). These laboratory journals contained Millikan's notations regarding which findings he thought were publishable and which were too far away from his expected value. His notebooks reveal that Millikan frequently found reasons to discard data when those values fell outside the anticipated range, but he did not examine the result as closely when the data conformed to his expected value. One could say that he knew what to look for and did so with passion.

On the other hand, it is easy to imagine that when an observer is so sure of the data that will be observed, in which direction they should be looking, and what the data imply, it would be very easy to miss something of interest. The history of science is full of examples of older scientists—presumably with more prior ideas—overlooking interesting findings because they simply do not correspond with their world view and expectations. One particularly fruitful example of this would be the long ranging debate about the cause of the demise of the dinosaurs at the end of the Cretaceous period. While all scientists agreed that dinosaurs met their end about 66 million years ago, many who preferred other explanations had trouble seeing that multiple lines of evidence pointed to an extraterrestrial impact. It was simply not part of their prior expectation that a huge object from space might have smacked the Earth, created cataclysmic fires generating massive amount of soot that in turn blocked sunlight for decades, and generally wrought havoc on food chains worldwide. Likewise, a previous generation of earth scientists could not imagine that the continents, in fact, did change position even when faced with the strong suggestion that South America and Africa really did embrace each other at some point in the past.

7.4 Considering the Challenges of Observations in Science Instruction

Certainly, the issue of making observations is a topic of considerable interest both in understanding how science is conducted and in appreciating the strengths and limitations of scientific methodology. So, it is no surprise that for much of the past century, science educators have advocated specific training in observational skills. Johnson (1942), for instance, reports that his department designed a program "to train students in observation and accurate recording" (p. 57). Norris (1984, 1985) provided an overview of the philosophical basis of observation and a definition of observational competence but this view was criticized by Willson (1987) who stated that "Norris failed to differentiate between two kinds of observation, theory-building and theory-confirming observation" (p. 283). Willson believed that science educators have neglected to distinguish the nature of observations made by expert scientists from those made by novice students. Even this distinction, while assisting science educators to see observation as a high-level process, omits mention of the role of expectancy in coloring the way in which observations are made both by students and by scientists.

One of the so-called "alphabet soup" curriculum projects in the United States, *Science: A Process Approach* (SAPA 1967), was designed to acquaint students with how science is done by suggesting that if students would understand and practice the skills of scientists both prior goals would be accomplished. To that end, the designers of S-ASA identified 13 skills—called process skills—seen as common investigative tools found across all science disciplines. Among these skills, observation was considered one of the most basic, an unfortunate assumption.

In their text on science teaching methods, Collette and Chiapetta (1994) made a rare reference to the challenges of observation in the education of future science teachers. They pointed out that what people observe depends upon their interests and that "false observations can occur when the senses provide the wrong information … [and that] the mind plays tricks on the observer…" (p. 38). They close their short section on observation by stating that "[a]though observation seems to be the most basic and fundamental of the inquiry skills, it is a complex activity that merits careful study in and of itself" (p. 38). Even as science educators pay more attention to the problems of observation, few have provided suggestions for what teachers or science methods instructors can do to examine observation in the classroom, to instruct students about the range of issues that impact observation, or to avoid the problems associated with this important process skill.

While few would argue that observation is an important science process skill, given what we know about observation, only those who are naive would characterize observation as basic. As mentioned, all observers have their own ideas about the way nature operates and this prior knowledge plays a role in the way in which students make observations. Teachers may defend the laboratory experience by stating that hands-on work gives students the opportunity to observe scientific phenomena for themselves, but observation of phenomena and interpretation of data are not simple tasks. There is no suggestion that schools should scale back the use of laboratory activities but rather we should help students understand that observation is not as straightforward as they perhaps believe. In doing this, we would be teaching students a valuable NOS lesson related to the *Human Dimension of Science*. In this concluding section, we will explore a real-world illustration of the impact of prior knowledge on observation by exploring a phenomenon known as the expectancy effect. As you will see, this is both a challenge and an opportunity.

7.5 Prior Knowledge and the Expectancy Effect in School Science

Expectancy is a label for an issue within what is called experimenter, observer, or investigator effect in the psychological literature and may be thought of as the outcome associated with the inevitable presence of prior knowledge on the part of an observer. Expectancy occurs when investigators, with no desire to misrepresent results, equate "what they think they see, and sometimes what they want to see, with what actually happens" (Lane 1960, p. 85).

According to Rosenthal (1976), the author of the most comprehensive treatise on this topic, there are two main classes of experimenter effects—biosocial and non-biosocial. In the biosocial realm, a subject of study may behave differently because of some characteristic of an observer. This result is primarily found in behavioral studies with humans but has been noted for other species including dogs and horses. Rosenthal reports that canines have been found to have differential heart rates when a scientist is visible to the animal. Investigator variables shown to interfere with expected results in human behavioral studies include the scientists' age, religion, gender, the degree of hostility, dominance or warmth, the level of acquaintanceship with the subject, and anxiety.

The category of experimenter effects of most interest to science educators are the nonbiosocial ones since these operate in all investigative settings not just in those that involve experiments with people and higher animals. Nonbiosocial experimenter effects include the interpreter effect, the effect of early data returns, and expectancy. The interpreter effect occurs when two or more individuals observe the same phenomenon but evaluate the results differently depending on their prior knowledge. Interpreter effects drive the expectation of the experimenter and influence what is observed, what is ignored as irrelevant, and what data are called into question, and ultimately what is published (Sheldrake 1995). The example of Millikan provided earlier might be thought of as an example of this effect.

In the case of early data returns, investigators' expectations about the eventual result are swayed by the nature of the first data gathered, an effect noted as early as 1885 (Rosenthal 1976). Early data returns can influence the investigator either toward or away from a given hypothesis. Returns which agreed with the predicted result strengthen the expectancy effect whereas weak returns may modify the original expectation, but both will tend to influence the observer and tend to be self-fulfilling prophecies. In science classes, it is common for students to collect a few data points and then become satisfied that they know the end results. Or, as Rosenthal (1976) states, "perhaps early data return that disconfirm the experimenter's expectancy leads to a revision of the expectancy in the direction of the disconfirming data obtained, thereby making it more likely that subsequent data will disconfirm the original hypothesis but support the revised hypothesis" (p. 196).

These effects may all play a role in the instructional laboratory, but the experimenter effect of most importance from a NOS perspective is that of expectancy—the idea that observers may "see" what they expect to see. Several studies of this type of biased observation have shown that if an expectation is created in an observer, the observation will be influenced. One interesting example is seen when researchers count the incidence of twisting in the common flatworm *Planaria*. Even among experienced observers, those told that they had "high-twisting" *Planaria* counted more twists than observers told they had "low-twisting" animals. This result occurred even though both "types" of worms were taken from the same batch of animals, all with the same characteristics (Cordaro and Ison 1963). Other experiments with rats labeled as "high-learning" or "low-learning" revealed a similar expectancy effect when these rats were timed running through mazes. Researchers reported that the "high-learning" animals ran the mazes faster than the "low-learning" rats even though all the rats, despite their label, were identical in their maze-running ability (Rosenthal and Fode 1963). Next, we will explore the problem in practice a discussion of data from a classroom experiment and conclude the chapter with the use of the classic old woman/young woman illusion to exemplify the point for students easily.

7.6 The Daphnia Dilemma: An Experimental Illustration of the Challenge of Prior Knowledge

Next, we will discuss a fascinating example of the role played by prior conceptions on students' ability to observe scientific phenomena in the laboratory with a common exercise in which students place stimulants and depressants on *Daphnia*[1] (a common freshwater crustacean) and measure changes in the animals' heart rate. Gray (1996) reported that the exercise did not seem to work as anticipated but stated that it might still be useful in encouraging discussion of the nature of scientific inquiry.

Perhaps the variable most likely explanation of the results was whether the students knew—or thought they knew—what was likely to occur in advance of the actual laboratory trial. This variable, which is called the expectancy effect, is likely known and accepted by members of the science education community, but surprisingly has rarely been a feature of research in science education (Hainsworth 1956, 1958). That is unfortunate given its importance. Observation is discussed and commonly included in science instruction as a common element in laboratory investigations but is only infrequently explicitly examined in school science or tied to the nature of science. A recent exception may be found in Lau and Chan (2013) who investigated ways to teach about "theory-laden" observation by telling some students that vitamin C can be destroyed by heating and telling other students that is cannot be and then having students analyze data with this prior notion in mind.

7.6.1 Methodology

This experiment began by securing a quantity of the freshwater crustacean, *Daphnia magna*, from a biological supply company. The animals were maintained in spring water and fed dried algae as recommended by the supplier for the duration of the investigation. *Daphnia* reproduce readily with a new generation of adults appearing every few weeks. The idea was quite basic; students would be asked to put various solutions (some labeled as stimulant, depressant, or unknown) on the *Daphia* and count the heartbeat to make judgments about the impacts of the

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[1] Daphnia are a common type of freshwater crustacean sometimes called water fleas because of the hopping motion made when they swim. Their transparent shells allow students to see through to the internal organs. The small *D. pulex* has been available for many years, but the much larger *D. magna* has increased in popularity due to the enhanced ease with which students can see key structures.

chemicals introduced. However, in all cases, the various solutions were nothing but pond water and would not be expected to have any physiological effect.

Several classes of biology students were recruited for this investigation. Subjects were all secondary school (ages 14–18) biology students in general biology representing 12 classes at two urban and two suburban schools. All ethnic groups were represented with some skew toward members of minority populations—primarily Hispanic. Males and females were equally represented.

Each pair of students received a set of three dropper bottles containing nothing but the same spring water in which the *Daphnia* lived made by filtering out the animals and debris. This water was put in the containers for each new trial. The use of the same water in which the animals lived made it highly unlikely that it would have any physiological effect when introduced to the animals later. Even though the dropper bottles contained nothing but the spring water in which the animals were reared, one of the bottles was labeled "Stimulant," one was labeled "Depressant," and the final bottle was labeled "Unknown." All dropper bottles and stock culture of *Daphnia* were maintained at the same temperature to ensure that temperature played no role in the experiment. Please note that throughout this paper, the contents of the experimental solutions are indicated in quotations because they consisted of nothing but water in which the animals lived. Students believed them to contain active ingredients.

The students were introduced to the exercise with a diagram of the anatomy of the animal, pointing out the heart and other structures. As an introduction, I discussed the correct technique for counting heartbeats and reviewed what a stimulant and depressant would likely do to the heart rate. Students were told that the stimulant was a weak solution of nicotine, that the depressant was a weak solution of alcohol, and that the unknown could be either nicotine, alcohol, or pond water. Students were assured that they were not being assessed and that the purpose of the exercise was to see if the laboratory activity worked properly. The investigator had a conversation with the students in advance about what was likely to happen to the heart rate of these animals exposed to stimulants and depressants.

The heart rate of *Daphnia* is quite high (approximately 270 beats per minute) and individual students who look at the beating heart while trying to count the beats easily became frustrated and lose count. Therefore, a team approach was devised in which one student would look at the beating heart through the low power microscope objective and gently tap in time with the beating heart. The other student did the actual counting. Pairs of students were given an animal on a depression slide. To keep the animal still, the *Daphnia* were held in place with a few cotton fibers floating in the water. One of the student investigators kept time with a clock that audibly signaled the end of 15 s. During this time, the second student counted and recorded the taps. The resting heart rate of the animal was measured for three 15-second intervals and recorded on a chart provided. Students practiced this counting skill before proceeding with the experimental trials.

Following the practice period, students placed one drop of the liquid labeled "Stimulant" on the animals. After 1 min (presumable to allow the "drug" to take effect), the heart rate was again counted during three trials. The students then placed that animal in a holding container, rinsed and dried the slide, and received a new animal for the second experiment. Again, the resting heart rate for the new animal was determined and the basic procedure was repeated using liquids labeled “Depressant” and, with a third fresh animal, the “Unknown.” Students recorded their findings on data sheets provided.

7.6.2 Results

In the first of the three experiments, students reported that the resting heartbeat of the *Daphnia* was approximately 240 beats per minute (bpm) when averaged over three 15-second trials (Table 7.1). Students reported an increase in the heart rate to 276 bpm on average after the introduction of what students thought was a stimulant. ($\Delta = 36$ beats per minute). This increase is significant ($t(138) = -10.9$, $p < 0.001$).

In the next trial, a new animal was used, the “depressant” was introduced, and the heart rate measured. In this case, the average resting heart rate was measured at 256 bpm which students said decreased to 235 bpm ($\Delta = -21$ beats per minute) with the chemical. This decrease is significant ($t(140) = 5.89$, $p < 0.001$).

In the final trial, the same protocol was followed. Another fresh animal was used, the “unknown” was introduced and the heart rate was measured again with a resting heart rate of 252 bpm on average. After introducing the “unknown,” students reported that the average heart rate was 260 bpm ($\Delta = 8$ bpm). This change is not statistically significant ($t(125) = -1.6$, $p =$ n.s.) as one would predict if the observers had no reason to expect a given result.

There were a few but quite interesting qualitative results noted when some students made comments while the experiment progressed. At various times in all classes a few students invariably asked why “nothing was happening.” This was an indication that students knew what was supposed to occur and were curious that it did not. This was balanced by another group of frequently-heard comments including: “Wow, look how fast the heart is beating!” with the introduction of the “stimulant,” or “[the heart] really slowed down,” after students put the “depressant” on the animal. Again, there were no active ingredients in any of the dropper bottles so any

Table 7.1 Pair-wise summary statistics and the results of paired *t*-tests for each of the experiment[a]

		Mean (per 15 s)	*N*	Std. Deviation	*t*	df (two-tailed)	Sig.
Pair 1	Resting Set 1	59.85	139	13.59	−10.900	138	$p < .001$
	“Stimulant”	69.07	139	17.61			
Pair 2	Resting Set 2	63.94	141	15.21	5.890	140	$p < .001$
	“Depressant”	58.68	141	15.76			
Pair 3	Resting Set 3	63.09	126	14.15	−1.600	125	n.s.
	“Unknown”	64.90	126	17.55			

[a] Note: the number of pairs of students differs because of missing data and the failure of one class to complete the investigation of the unknown. The resting values are calculated separately because they were for different animals (three per trial) in each experiment

changes to the observed heartbeat were in the students' minds, not in the physiology of the daphnia.

7.7 Discussion and Conclusion

This experiment illustrated the impact of prior knowledge on students' measurement of the heart beat rate in *Daphnia*. When students were confronted with the expectation that certain chemicals were likely to have a given physiological effect on an animal, they seemed willing to report seeing such an effect, even though such a result was impossible.

There are at least two variables that might have confounded the result including lack of skill and lack of veracity in the completion of the measurement task. To address these issues, the study design incorporated a control designed to demonstrate that students do know how to achieve the correct result when their perceptions are not influenced by prior knowledge. This control was the "unknown" (just spring water) that students would have no reason to effect a change when applied to the *Daphnia*. The lack of a statistical difference between the results before and after the administration of the "unknown" shows that the average student teams could make accurate counts of heart rate. It is true that some student teams thought they perceived a stimulation effect and others a depressant effect following the application of the "unknown," most teams reported that the "unknown" had no effect. This is exactly what one would predict when the observers had no reason to anticipate any particular result. The "unknown" was nothing more than pond water and should cause no increase or decrease in heart rate.

Another potentially confounding variable was the possibility that some students wanted to provide the correct result and, therefore, cheated. There is no way to ensure that this did not happen, but the experiment was designed to minimize this effect. Students were told to record whatever they observed no matter what they thought might happen. We responded to any student exclamations of surprise when a result seemed at odds with the expectation by telling them that, sometimes, this might be an individual reaction. Finally, since the students themselves were not assessed and the activity was not part of a graded class assignment, it seemed unlikely that students would be motivated to produce results other than those perceived.

7.7.1 Implications and Recommendations

The implications of these findings are profound and call into question the assumptions science teachers likely make about how well laboratory and other hands-on experiences communicate science content. Thus, there are at least two types of recommendations to be made.

Teachers must no longer assume that because students report the desired results that they really observed what the exercise was designed to demonstrate. By acquainting students with the issue of expectancy, they may be less inclined to fall victim to the problem, or at least will be aware of the limits of observation in general. However, as Rosenthal (1976) found, avoiding the problem is difficult even for professional scientists. Of course, one could suggest that the advantage of expectancy, since students are likely to think that they have seen the desired result even if their work or the design of the activity would have made the teacher-desired result unlikely.

Perhaps doing laboratory work *before* students are fully aware of what is supposed to happen may minimize the expectancy effect. Interestingly, the recommendation that laboratory investigations should precede lecture have been offered for many years (McComas 2005). Also, Boghai (1978), Raghubir (1979), Bishop (1990), Ivins (1985), and Leonard (1980) have shown that this technique is useful in that students exhibit higher levels of cognitive ability, independent functioning, and more fully enjoy laboratory experiences when such activities are more investigatory and less confirmatory than typical ones.

Another interesting issue associated with this activity is the opportunity that it can provide to demonstrate this important effect on students and then engage in a discussion of this aspect of the nature of science. Having students repeat the experiment would be a powerful introduction to the issue of observation and the role of prior knowledge in science generally. Recounting the stories of Millikan and the admonition of Darwin could prove illustrative in this case. Issues that could be discussed might include whether:

- It is even possible to observe a specific phenomenon without expectation of what be seen.
- It is useful to make observations without some expectation or prior speculation.
- Students can operate like scientists while conducting experiments in the school science laboratory.

This last issue was addressed by Hanson (1958) who stated that unless one is trained within a science discipline it is impossible to view the world through the eyes of a scientist. This comment stems as much from the observer-effect as it does from recognition of the controlling paradigm in which the observation was made. When commenting on the ability of a nonscientist to observe a phenomenon, Hanson remarked, “the elements of the visitor’s field, though identical with those of the physicist, are not organized for him as for the physicist” (p. 17).

While it is unlikely that the expectancy effect would cause students to “see” blue litmus paper turn red unless it really did, or report crayfish remnants in the stomach of a dissected frog unless such remains exist. However, in any laboratory or inquiry activity in which subjectivity is involved, expectancy can play a role. Expectancy may complicate exercises that involve almost any sort of measurement such as counting the swings of a pendulum, timing a ball rolling down an inclined plane, titrating, using a color card to determine the pH of a solution, or drawing the line of best fit through a data field.

To conclude, perhaps we should reconsider the admonition of Frances Bacon—one of the forefathers of modern science—that we apply pure induction and observe without bias or preconceptions. We now realize two things making observations in the way recommended by Bacon: (1) it is not possible and even more importantly (2) may not be desirable. As Pasteur said in an 1854 lecture *Dans les champs de l'observation le hasard ne favorise que les esprits prepares.* "Where observation is concerned, chance favors only the prepared mind." What this means, of course, is that prior knowledge is just as valuable in scientific discovery as it is inevitable and potentially challenging, and students must gain understanding about expectancy, confirmation bias, theory-laden observation, and the range of issues that make science a subjective endeavor.

7.7.2 A Note About Ethical Considerations

We recognize the ethical considerations in this kind of research where students were deliberately told an untruth. All teachers involved in the study were aware of its true nature at the beginning, and several indicated that they planned a follow up lesson that would use the result of our investigation as an opportunity to engage student in a discussion of observation. One teacher believed that since the students thought they had seen what they were supposed to have seen, they were better off thinking that they had, in fact, observed the results reported.

It should be clear that no harm could come to the students whether or not they were told the true purpose of the experiment reported here. Those students who were told of the full story would gain a valuable lesson about NOS while those not so informed would still have learned a valuable lesson regarding in the effects of certain chemicals on *Daphnia* physiology.

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A. Appendices

Appendix A: The Use of Optical Illusions to Illustrate "Theory-Based" Observations

To illustrate the challenges inherent in "theory-based" observation, instructors may find it useful to secure a wide variety of optical illusions, particularly ones where two images are cleverly blended together in what are sometimes called ambiguous figures. One of these (Fig. 7.1) is the classic often referred to as *Young Woman/Old*

Fig. 7.1 Hill (1915). The classic *My Wife and My Mother-in-Law* ambiguous figure

Woman or *My Wife and My Mother in Law*. The origin of this figure is itself somewhat ambiguous with reports that it first appeared in a different form as a nineteenth century German postcard and was then redrawn by illustrator William Hill and published in the magazine *Puck*. Therefore, it seems reasonable to cite this as Hill (1915).

For those who have not explored this image previously you will have no expectation. Some may first see a young woman who seems to be turning her face to the right. She is wearing a necklace and has a feather on her headscarf. It is just possible to see her left ear and chin, a bit of her left eyelash and her nose. With another look, the image may transform into an older woman who is turning her head somewhat to the left. The necklace of the young woman is now the woman's mouth, the girl's chin is now the nose of the older woman and what was previous the left ear becomes the older woman's eye. They both share a while billowy headscarf, feather, and black hair.

To introduce the topic of "theory-based" observation to students not previously familiar with this image, a teacher could hand out cards to half the students saying, "Do you See the Old Woman in this Image?" and cards to the other half saying, "Do you See the Young Woman in this Image?" and then project the image to the entire class. Then ask the students to raise their hand if they see the Young Woman (or Old Woman, it doesn't matter) and note which hands are raised. Certainly, there will be some who see the "wrong" image, have already seen this picture or can't see either.

Generally, students who were "clued" by the statement on the card to look for the Old Woman will see that image most easily and vice versa. Having a range of such images and related optical illusions ready to share with the class along with two sets of cards directing students to look for different aspects of those images will provide some useful case material to engage students in a discussion of the role of prior expectations in observation. Fortunately, there are many such images available online for use in this fashion.

Appendix B: A Practical Example of Expectancy in Chemistry Class

In a series of lessons in chemistry class students explored some of the variables that affect the rate of gas production during electrolysis. One variable they noted was that the process occurs more quickly as the concentration of the electrolyte increased.

Next, I used this now-prior knowledge to reinforce the technique of electrolysis while introducing some of the problems of observation and thus discuss an important NOS element along with the traditional chemistry content. To extend this lesson and incorporate the expectancy effect, a bit of deceit was necessary.

I made a solution of sodium carbonate and poured that into three different containers. Each container was labeled a different concentration when in fact they were all the equal. I performed a demonstration for the students using a standard electrolysis set-up. I performed the demonstration three times, each with a supposedly different electrolyte solution and asked students to write down their observations. I mentioned the supposed concentration of electrolyte each time I did the demonstration and asked students simply to note anything of interest. They could have noted the time involved and the volume of gas produced if interested or simply watched from a qualitative perspective.

Students in each said things like “Oh wow look at how fast it’s going now!” However, the process was going at the same speed every time because the electrolyte concentration was identical in all three trials.

They knew from previous experiments that as the concentration of the electrolyte is increased the electrolysis rate also increases; so many students “saw” what they expected to see. Their expectations caused them to perceive an increase in reaction rate. Had they measured the amount of gas produced and noted the time involved they would have seen that all three trials produced the same amount of gas per unit time.

After the demonstration we had a conversation about the challenges of observation and the expectancy effect. Many of the students were amused that this could happen to them. Although I did hear one student remark, “I didn’t think anything special was happening, but everyone was saying it was, so I kept my opinion to myself.”

Contributed by Kent Woodard, Chemistry Teacher.
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References

Beveridge, W. I. B. (1957). *The art of scientific investigation*. New York: Norton.

Bishop, R. D. (1990). *The effect of laboratory activity ordering on achievement and retention*. Unpublished doctoral dissertation, Southern Illinois University, Edwardsville.

Boghai, D. (1978). A comparison of the effects of laboratory and discussion sequences on learning college chemistry. *Dissertation Abstracts International, 39*, 6045A.

Boring, E. G. (1950). *A history of experimental psychology* (2nd ed.). New York: Appleton Century Crofts.

Brewer, W. (2015). Perception is theory-laden: The naturalized evidence and philosophical implications. *Journal of general philosophy of science, 46*, 121–138.

Brewer, W. F., & Lambert, B. L. (2001, September). The theory-ladenness of observation and the theory-ladenness of the rest of the scientific process. *Philosophy of Science, 68*(53), S176–S186. https://doi.org/10.1086/392907.

Collette, A. T., & Chiapetta, E. L. (1994). *Science instruction in the middle and secondary schools*. New York: Macmillan Publishing Company.

Cordaro, L., & Ison, J. R. (1963). Observer bias in classical conditioning of the planarian. *Psychological Report, 13*, 787–789.

Darwin, C. R. (1850). *Darwin correspondence project* (www.darwinproject.ac.uk). March 4 letter to Charles Henry Lardner Woodd (DAR 148:375).

Duschl, R. (1985). The changing concept of scientific observation. In R. Bybee (Ed.), *NSTA yearbook: Science, technology and society* (pp. 60–69). Arlington: National Science Teachers Association.

Franklin, A. (1981). Milliken's published and unpublished data on oil drops. *Historical Studies in the Physical Sciences, 11*, 185–201.

Franklin, A. (2015). The theory-ladeness of experiment. *Journal of general philosophy of science, 46*, 155–166.

Gould, S. J. (1994). The geometer of race. *Discover, 15*(11), 67–68.

Gray, D. (1996). Using Daphnia to teach critical thinking about biological research. *The American Biology Teacher, 58*(3), 160–161.

Hainsworth, M. (1956). The effect of previous knowledge on observation. *The School Science Review, 37*, 234–242.

Hainsworth, M. (1958). An experimental study of observation in school children. *The School Science Review, 39*, 264–276.

Hanson, N. R. (1958). *Patterns of discovery*. Cambridge: Cambridge University Press.

Hill, W. E. (1915). *My wife and my mother-in-law*. New York: Puck Press.

Ivins, J. E. (1985). *A comparison of the effects of two instructional sequences involving science laboratory activities.* Unpublished doctoral dissertation, University of Cincinnati, Cincinnati, OH (ERIC Document Reproduction Service, No. ED 259 953).

Johnson, M. L. (1942). Biology and training in observation. *School Science Review, 23*, 56–57.

Lau, K., & Chan, S. (2013). Teaching about theory-laden observation to secondary students through manipulated lab inquiry experience. *Science & Education, 22*, 2641–2658.

Lane, F. W. (1960). *The kingdom of the octopus*. New York: Sheriden.

Leonard, W. H. (1980). Using an extended discretion approach in biology laboratory investigations. *The American Biology Teacher, 42*(7), 338–348.

Mayr, E. (1991). *One long argument*. Cambridge, MA: Harvard University Press.

McComas, W. F. (2005). Laboratory instruction in the service of science teaching and learning. *The Science Teacher, 72*(7), 24–29.

McComas, W. F., & Moore, L. S. (2001). The expectancy effect in the secondary school laboratory: Issues and opportunities. *American Biology Teacher, 63*, 246–252.

Nickerson, R. S. (1998, June), Confirmation bias: A ubiquitous phenomenon in many guises, *Review of General Psychology, 2*(2): 175–220. https://doi.org/10.1037/1089-2680.2.2.175.

Norris, S. (1984). Defining observational competence. *Science Education, 68*(2), 129–142.

Norris, S. (1985). The philosophical basis of observation in science and science education. *Journal of Research in Science Teaching, 22*(9), 817–833.

Raghubir, K. P. (1979). The laboratory investigative approach to science instruction. *Journal of Research in Science Teaching, 16*(1), 13–18.

Rosenthal, R. (1976). *Experimenter effects in behavioral research* (Enlarged Edition). New York: Irvington Publishers.

Rosenthal, R., & Fode, K. L. (1963). The effect of experimenter bias on the performance of the albino rat. *Behavioral Research, 8*, 183–189.

SAPA (*Science – A Process Approach*). (1967). Washington, American Association for the Advancement of Science.

Schindler, S. (2013). Theory-laden experimentation. *Studies in the history and philosophy of science, 44*, 89–101.

Shapare, D. (1982). The concept of observation is science and philosophy. *Philosophy of Science, 59*, 485–525.

Sheldrake, R. (1995). *Seven experiments that could change the world*. New York: Riverbend Books.

Tracy, G. (2018). Learning to see. *American Scientist, 106*(4), 242–249.

Willson, V. L. (1987). Theory-building and theory-confirming observation in science and science-education. *Journal of Research in Science Teaching, 24*(3), 279–284.