ACTIVITY 5

Addressing Uncertainty in Science

READING

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ACTIVITY SUMMARY

Students read about the Harvard Six Cities Study, one of the first large studies on the health effects of poor air quality, and synthesize ideas previously introduced in the unit, including scientific uncertainty and sources of error. Students learn how scientists plan for and reduce errors in experimental design and data collection. They learn that confidence intervals and confidence levels are methods scientists use to communicate uncertainty in their work.

ACTIVITY TYPE
READING

NUMBER OF
40–50 MINUTE
CLASS PERIODS
1-2

KEY CONCEPTS & PROCESS SKILLS

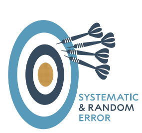
1 Uncertainty in data is often a result of errors. Scientific errors can be random or systematic and can lead to conclusions that are less likely to be correct.

2 Scientific methods can reduce sources of uncertainty. Techniques to reduce random error include taking repeated measurements and averaging across many samples. Techniques to reduce systematic errors include calibrating equipment more carefully and designing investigations to control for other factors that could influence the results (*confounds*).

3 Confidence intervals, confidence levels, and error bars describe the uncertainty of data and the probability that data are accurate.

NEXT GENERATION SCIENCE STANDARDS (NGSS) CONNECTION:
Consider limitations of data analysis (e.g., measurement error, sample selection) when analyzing and interpreting data. (*Science and Engineering Practice: Analyzing and Interpreting Data*)

CONCEPTUAL TOOLS



VOCABULARY DEVELOPMENT

confidence interval
the range of data expected to contain the true value

confidence level
a statistical measure of the probability that the true value is within a specified range

confound
a factor that can distort or hide the relationship between two variables being investigated in a study

TEACHER BACKGROUND INFORMATION

Harvard Six Cities Study

The Harvard Six Cities Study, published in 1993, was a landmark investigation into the relationship between air pollution and public health. Researchers tracked over 8,000 participants from 6 U.S. cities—Portage, Wisconsin; Topeka, Kansas; Watertown, Massachusetts; St. Louis, Missouri; Kingston-Harriman, Tennessee; and Steubenville, Ohio—over 14–16 years and analyzed the effects of long-term exposure to particulate matter (PM2.5). The study revealed a strong association between higher levels of air pollution and increased mortality, particularly from cardiovascular and respiratory diseases. Individuals in the most polluted city, Steubenville, Ohio, faced a 26% higher risk of death compared to those in the least polluted city, Portage, Wisconsin. Eventually, the study was extended to collect data through 2009. The results of the extended study confirmed the earlier findings.

This research was instrumental in demonstrating that even low levels of air pollution, previously considered safe, could significantly impact health. It led to more stringent air quality standards in the United States under the Clean Air Act, emphasizing the need to control fine particulate pollution. The study also set a new benchmark for epidemiological research by combining long-term population health data with environmental exposure metrics, influencing policy and furthering our understanding of the health risks posed by air pollution.

Variability, Confidence Levels, and Confidence Thresholds

After reducing sources of random error and systematic error as much as possible, one way that scientists estimate the remaining uncertainty of their data is by considering its variability—how different all the individual data points in a group are from one another and their calculated average. (The term *variability* is not used in the student materials; however, Activity 6 refers to how spread out or close together the data points are from one another.)

Statistical measurements help scientists consider the probability that an effect they measured was due to chance by considering variability, the number of samples, and the size of the effect (for instance, the difference between two experimental groups). A higher variability of the data and collecting less samples increase the probability that the results were due to chance, whereas a larger size of the observed effect decreases it. This probability is interpreted as a confidence level for how likely the observed effect is real. Most importantly, scientists require this confidence rating to meet a certain level of confidence, known as a *confidence threshold*. Typically, experimental results are only shared and accepted by other scientists when they have a calculated confidence level that is equal to or higher than 95%.

How can I reduce uncertainty? →

Correct for systematic errors and random errors!

How much uncertainty is left? →

Measure the variability of the data.

Is my result just from chance? →

Use the variability, number of samples, and size of the effect to calculate the probability that it was caused by chance.

How sure am I?

If that chance probability is low enough, then my confidence is high enough (over 95%) to make a conclusion.

MATERIALS & ADVANCE PREPARATION

FOR EACH STUDENT

- STUDENT SHEET 5.1 "Anticipation Guide: Scientific Uncertainty"
- STUDENT SHEET 5.2 "DART: Examples of Scientific Uncertainty"

TEACHING NOTES

Suggestions for **discussion questions** are highlighted in gold.

Strategies for the **equitable inclusion of diverse students** are highlighted in mint.

GETTING STARTED (10 MIN)

1 **Students complete the "Before" column of Student Sheet 5.1, "Anticipation Guide: Scientific Uncertainty."**

- Use the Anticipation Guide to elicit students' initial ideas about scientific uncertainty and sources of error. Student Sheet 5.1, "Anticipation Guide: Scientific Uncertainty," provides a preview of science concepts in this activity. An Anticipation Guide gives students an opportunity to explore their initial ideas and revisit and modify them at the end of the activity. Be sure students understand that they should complete only the "Before" column for the statements at this time; they will have a chance to revisit these statements after the reading to see whether their ideas have changed. For more information on an Anticipation Guide, see Appendix 1: Literacy Strategies.
- While an Anticipation Guide supports sensemaking, it requires additional reading and interpretation and may need to be modified for some student populations, such as emerging multilingual learners and neurodiverse students. You may wish to complete Student Sheet 5.1 as a class, use it at the end of the activity to summarize key ideas, or use it as a formative assessment of students' learning.

PROCEDURE SUPPORT (40 MIN)

2 **Hand out Student Sheet 5.2, "DART: Examples of Scientific Uncertainty."**

Explain to students that DART stands for a directed activity related to text that supports students' understanding of the material. It supports reading comprehension and critical thinking by having students interact with and manipulate the information they are reading. For more information on a DART, see Appendix 1: Literacy Strategies.

3 **Students complete the reading.**

- Have students read the text. If you have begun a word wall, support students, particularly emerging multilingual learners, in sensemaking and language acquisition by adding the terms c*onfidence lev-*

el, *confidence interval*, and *confound*. Provide an example of a confound, such as the pre-existing health conditions that might have influenced the health results in the Six Cities Study, as needed.

- Circulate around the room and check in with students as they use the DART strategy to decode scientific ideas and construct meaning as they read. You may need to clarify that a confound is a type of systematic error.
- Students should fill out Student Sheet 5.2 as they read. Point out that students are expected to provide examples of scientific errors in the first column. After reading, students can compare ideas and responses with another student. A Sample Student Response to Student Sheet 5.2 is provided at the end of this activity. In order to include all examples from the unit so far, it contains a more complete response than should be expected from most students.

SYNTHESIS OF IDEAS (20 MIN)

4 Students complete the "After" column on the Anticipation Guide.

After students complete the reading, direct them to complete the "After" column on Student Sheet 5.1. Discuss student responses as a class to ensure that all students understood the key concepts of the activity. A sample student response is shown at the end of this activity.

5 Review main ideas from the reading.

- Emphasize the key ideas about random errors and systematic errors and how scientists try to identify and reduce these types of errors in their work. Use Connections to Everyday Life item 3 to discuss how random errors and systematic errors can affect scientific data.
- Build Understand item 2 is a high-level question that involves identifying confidence intervals in a graph. You may wish to do this as a class or use pair-share and round-robin approaches to encourage all students to participate.

6 Lead a class discussion on understandings about science in society.

- As a class, discuss Connections to Everyday Life item 5. Science tries to get closer to the truth by testing ideas and making sure those ideas are supported by evidence. Depending on the available data, explanations may be incomplete or even incorrect. Scientists have to modify or change their ideas when faced with new evidence. When a lot of evidence points to the same conclusion, it reduces the uncertainty in a scientific conclusion. That is why it is important for scientists to consider sources of scientific uncertainty and how they could be affecting their data and conclusions. In this way, scientific uncertainty can be reduced and/or described. One way scientists communicate levels of scientific uncertainty is through confidence levels and confidence intervals.

- Finish the activity by revisiting the Guiding Question. Ask, How do scientists reduce uncertainty in science? Use responses to this question to formatively assess the key concepts and process skills related to random errors and systematic errors and methods to reduce these sources of scientific uncertainty. Student responses will vary but may include examples of scientific techniques from the reading, such as reducing random error by taking more data and averaging samples and reducing systematic error by calibrating equipment and careful experiment design.

EXTENSION (10 MIN)

7 **Use the Extension as an opportunity for advanced learning.**

The Extension provides an opportunity for students to consider ways in which local air quality can be improved by finding out more about the work being done in Louisville, Kentucky, by visiting the Green Heart Louisville Project's HEAL Study website. Encourage students to consider the role of community-based science in improving local health and well-being.

SAMPLE STUDENT RESPONSES

BUILD UNDERSTANDING

1. **Researchers want to determine if reducing indoor air pollution can affect the severity of flu symptoms. The first 100 volunteers to sign up are assigned to a control group and given a device that circulates indoor air. The next 100 volunteers are assigned to an experimental group and given a device that filters indoor air pollutants before circulating the air. The researchers track the severity of flu symptoms in each group and record the number of days it takes each person to recover. At the end of the study, the researchers measure the overall health of each patient.**

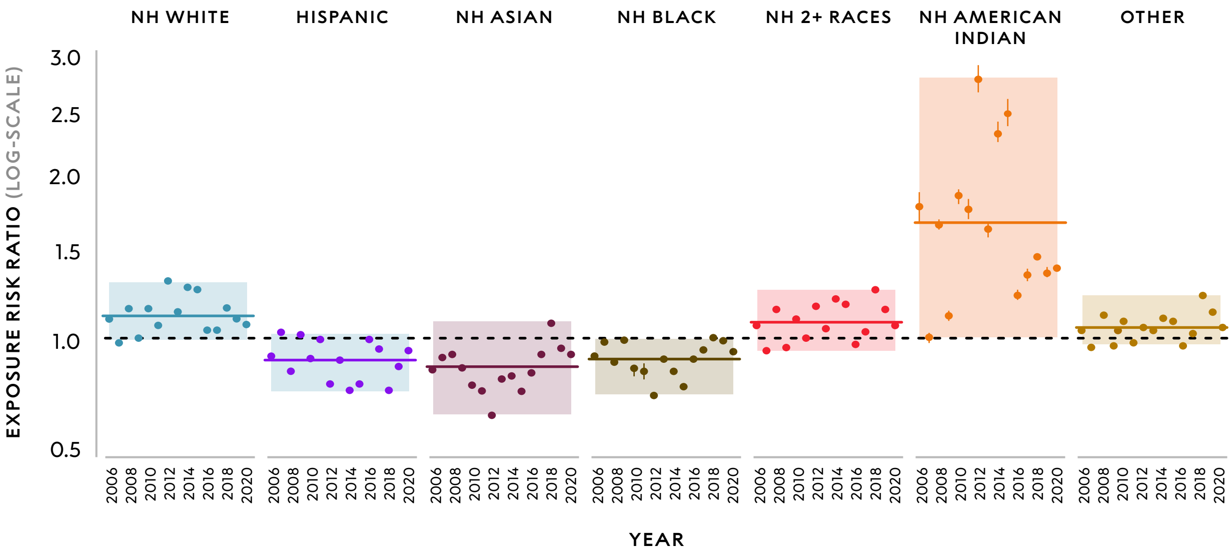
   Identify at least two scientific errors in the design of this study and explain how to improve the design to correct for these errors.

   One source of scientific error is assigning people to a group based on when they arrived and signed up. What if people arriving earlier were healthier than those arriving later? This would be a confound (a source of systematic error). The design could be improved by randomly assigning people to a group.

   Another source of scientific error could be differences between the amount of indoor air pollution in the homes of each participant. This could be a source of random error, since each participant has different living conditions. The design could be improved by monitoring the indoor air pollution levels in each person's home and comparing the averages.

2. **Figure 5.3 shows the average wildfire smoke exposure risk for different ethnic groups in California. The shaded areas of the graph represent a 95% confidence interval for each group's data set.**

FIGURE 5.3
Wildfire Smoke Exposure, in California, 2006–2020



a **Explain what a 95% confidence interval means in terms of this specific data.**

For this data, a 95% confidence interval means that if the researchers repeated this study 100 times, the results would fall within the shaded range 95 times.

b **What conclusions can you make about the data?**

I can conclude that some populations, such as white and Native American, have an increased exposure risk to wildfires, while other populations have a decreased exposure risk. The Native American population had the highest average risk.

c **The graph for the Native American population (labeled on the graph as "Non-Hispanic American Indian") has the largest confidence interval. How does this affect the amount of certainty you have in the conclusions you make about the graph?**

The large confidence interval means that in order to achieve 95% confidence level, there needs to include a bigger range of values. This means that there is more uncertainty in the Native American data set because the data points are more spread out. This makes me less certain about what the actual risk to the Native American population is—it could be as low as 1 and as high as 2.7.

CONNECTIONS TO EVERYDAY LIFE

③ **Johan wants to see if drinking more water will help clear up his acne. He decides to experiment by drinking 8 glasses of water every day for a month. He tracks his skin's appearance by taking pictures daily and noting the number of pimples. By the end of the month, Johan observes a lot less acne than at the beginning of the month.**

The following things happened during his experiment. Explain whether each is related to random error, systematic error due to equipment or experiment design, or a systematic error due to a confound. Explain how each might have affected his results.

a **Changes in weather, schedule, and diet resulted in several days when Johan drank more than or less than 8 glasses of water in a day.**

Factors such as weather, schedule changes, and diet were sources of random error because they happened unexpectedly. For example, if there was a really hot day, or if Johan ate a lot of salty chips, maybe he drank more water than usual. This might reduce how certain he could be in his results over time, since he didn't drink the same amount every day.

b **Johan didn't always use the same glass when he drank the 8 glasses of water. On some days, he used a smaller glass.**

This would lead to a systematic error due to equipment. On the days he used a smaller glass to drink 8 glasses of water, he drank less water than on the other days. This might reduce how certain he could be in his results over time, since he didn't drink the same amount every day.

c After 2 weeks, Johan ran out of face soap, so he bought a different brand of face soap.

Switching brands of face soap halfway through the month created a systematic error due to a confound. Now it is difficult to know whether Johan's improved skin was due to drinking more water or using a new face soap. It could just be that his new face soap is better at treating acne than his old one, but it's hard to tell.

④ How would you redesign Johan's experiment from item 3 to reduce sources of scientific uncertainty in his data?

Some ways to redesign the experiment might be to make sure Johan uses the same face soap throughout the experiment so the effects are constant. Johan can also set a minimum amount of water to drink, measured by volume—for example, 2 liters—instead of relying on the number of glasses, so the amount of water he drinks will be more constant.

⑤ American physicist and Nobel Laureate Richard Feynman said, "When a scientist…has a hunch as to what the result is, he [or she] is uncertain. And when he is pretty…sure of what the result is going to be, he is still in some doubt. Scientific knowledge is a body of statements of varying degrees of certainty—some most unsure, some nearly sure, but none absolutely certain."

Discuss with your class how uncertainty in science can sometimes mislead people into thinking that science cannot provide trustworthy information. How would you address this issue when talking to someone who says that science does not provide true information?

I would say that scientists have to make the best conclusions and explanations that they can with incomplete information. That's why it is important to consider sources of scientific uncertainty and how they could be affecting data and conclusions. Scientists have to accept the fact that they could be wrong and may need to change their thinking when faced with new evidence.

Sometimes when people hear that science isn't 100% sure about everything, they might think that science can't be trusted at all. But science is about finding the best answers based on the available evidence. I would explain that scientists try to get closer to the truth by testing ideas and making sure their ideas are supported by evidence. Scientists improve their understanding step by step. It doesn't mean science is wrong—it's just how science works.

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STUDENT SHEET 5.1	ANTICIPATION GUIDE: SCIENTIFIC UNCERTAINTY	NAME

In the "Before" column, mark whether you agree (+) or disagree (–) with each of the following statements. Then complete the reading. In the "After" column, mark whether you agree (+) or disagree (–) with the statements. Under each statement you agree with, explain how the activity gave evidence to support or change your ideas. Under each statement you disagree with, write and explain a corrected statement.

BEFORE	AFTER	
		1 Scientific uncertainty decreases as more data are collected and analyzed.
		2 Scientists are able to get rid of all sources of error in their data if they design their experiments carefully enough.
		3 Systematic error in data is a result of unpredictable changes in the environment.
		4 Identifying sources of error in an experiment makes conclusions about the data invalid.
		5 All sources of scientific error are a result of people making mistakes in data collection.
		6 Sometimes an unidentified factor can affect study results and make it harder to determine the true cause of an observed effect.
		7 Scientists use confidence levels and confidence intervals to communicate how sure they are about their results.
		8 Scientific uncertainty in experimental data means the science is unreliable.

STUDENT SHEET 5.1 | ANTICIPATION GUIDE: SCIENTIFIC UNCERTAINTY | NAME SAMPLE STUDENT RESPONSE

In the “Before” column, mark whether you agree (+) or disagree (–) with each of the following statements. Then complete the reading. In the “After” column, mark whether you agree (+) or disagree (–) with the statements. Under each statement you agree with, explain how the activity gave evidence to support or change your ideas. Under each statement you disagree with, write and explain a corrected statement.

BEFORE	AFTER	
	+	1 Scientific uncertainty decreases as more data are collected and analyzed. *Scientific uncertainty due to random error decreases as more data are collected. The example from the reading was how the Six Cities Study collected data over many years and averaged the results to reduce uncertainty in the conclusions.*
	–	2 Scientists are able to get rid of all sources of error in their data if they design their experiments carefully enough. *Scientists are not able to get rid of all sources of error. There will always be some uncertainty due to random error.*
	–	3 Systematic error in data is a result of unpredictable changes in the environment. *Random error in data is a result of unpredictable changes in the environment. Systematic error is not due to unpredictable changes but by a consistent error that affects the results.*
	–	4 Identifying sources of error in an experiment makes conclusions about the data invalid. *Identifying sources of error in an experiment reduces uncertainty about the conclusions from the data. According to the reading, knowing the sources of error in an experiment can help you understand the limitations of the data.*
	–	5 All sources of scientific error are a result of people making mistakes in data collection. *Scientific error is not only a result of people making mistakes. Random error is due to unpredicted changes or chance, while systematic error can be due to experiment design and equipment problems.*
	+	6 Sometimes an unidentified factor can affect study results and make it harder to determine the true cause of an observed effect. *An example is the confounds in the Six Cities Study. There were confounds related to the health conditions of the study participants, like their history of smoking or diet. These may have affected their life expectancies more than air quality.*
	+	7 Scientists use confidence levels and confidence intervals to communicate how sure they are about their results. *If a scientist has a higher confidence level, it means that their results will fall within an expected range more often.*
	–	8 Scientific uncertainty in experimental data means the science is unreliable. *Scientific uncertainty in experimental data does not mean that science is unreliable. Scientists can still make useful conclusions from data even if they can’t be 100% sure about the data.*

STUDENT SHEET 5.2	DART: EXAMPLES OF SCIENTIFIC UNCERTAINTY	NAME

EXAMPLES OF TYPES OF SCIENTIFIC ERROR FROM THE READING	EXAMPLES OF THIS TYPE OF ERROR FROM PREVIOUS ACTIVITIES	METHODS FOR REDUCING SCIENTIFIC UNCERTAINTY
Random error		
Systematic error		
Confound (a type of systematic error)		

EXAMPLES OF TYPES OF SCIENTIFIC ERROR FROM THE READING	EXAMPLES OF THIS TYPE OF ERROR FROM PREVIOUS ACTIVITIES	METHODS FOR REDUCING SCIENTIFIC UNCERTAINTY
Random error *Air pollution can be affected by factors that can affect AQI in unexpected ways, like fluctuating weather, winds, and industrial pollution.* *Unexpected air currents near air sensors can cause random fluctuations in AQI readings.*	***Activity 3*** *Looking at areas with more air sensors vs. less air sensors: The area with less air sensors might have data that are more affected if there is random error because there are less data points.* ***Activity 4*** *There could be random error involved in counting the number of particulates on the petri dish, as well as the petri dishes placed in the same location may not have the same count of particulates.*	*Taking more data points, measuring data over long periods of time, and averaging data can reduce scientific uncertainty due to random errors.*
Systematic error *AQI measurements can be affected if the equipment is not working correctly, leading to over or under measurement of the AQI.* *If air sensors are placed in a location that has less air pollution than where the study participants live, their exposure might be underestimated.*	***Activity 3*** *We looked at data from low-quality and high-quality air sensors. The low-quality air sensors may have been consistently under measuring or over measuring the AQI.* ***Activity 4*** *There could have been systematic error in our experiment due to design. For example, we placed our petri dish next to an air vent when we could have placed it in the middle of the room, which would have given a more representative reading of the particles in the room.*	*Identify sources of systematic error and try to correct or remove them by calibrating or repairing equipment, improving experiment design.*
Confound (a type of systematic error) *Smoking history or dietary factors could have affected the health of study participants, making it difficult to be sure that air quality was the factor responsible for the reduced life expectancy results.*	***Activity 2*** *We investigated indoor air quality but determined that outdoor air quality can have a big effect on indoor air quality.* ***Activity 3*** *Some locations might have factors like unexpected construction projects going on, which temporarily affect the air quality.* ***Activity 4*** *The petri dish was placed in the garage without realizing that lint from the dryer is adding particles to the petri dish.*	*Try to improve experiment design, consider the effects of the confound on the data and conclusions.*