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The Role of Anomalous Data in Theory Change: A Cognitive Analysis

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ABSTRACT

Many science educators have advocated the use of anomalous data--data that contradict students' preinstructional theories--to promote theory change. Many students, however, discount anomalous data so as to preserve their current theories. In order to understand the process of theory change in science classes, it is essential to understand students' responses to anomalous data. The purpose of this paper is to present a framework for understanding how people respond to anomalous data and why they respond as they do. First, I present a taxonomy of seven responses to anomalous data: (a) ignoring the data, (b) rejecting the data, (c) excluding the data from the domain of the current theory, (d) holding the data in abeyance, (e) reinterpreting the data, (f) peripheral theory change, and (g) theory change. Second, I present an analysis of nine factors that are hypothesized to influence which of these seven responses an individual will choose. I support these analyses with evidence from the history of science, from psychology, and from science education.

INTRODUCTION

During the past 20 years, both cognitive psychologists and educators have come to understand the crucial role of pre-existing knowledge in the acquisition of new knowledge. In order to understand knowledge acquisition, it appears to be necessary to specify in detail: (a) the structure and content of current knowledge, (b) the structure and content of the new information, and (c) the relationship between current knowledge and the new information (e.g., the new information may simply repeat current knowledge; the new information may be new but generally consistent with current knowledge; or the new information may contradict current knowledge).

In many cases of fundamental knowledge change, the relationship between current knowledge and new information is one of contradiction. The literature on children's naive theories or alternative frameworks has documented that children's preinstructional ideas frequently conflict with the ideas that they are supposed to learn in science classes (e.g., Driver, Guesne, & Tiberghien, 1985). Similarly, research in the history of science and the sociology of science shows that scientists must frequently grapple with ideas conflicting with their own (e.g., Mulkay & Gilbert, 1982; Thagard, 1992).

A particularly important form of anomalous information is anomalous data. Anomalous data have played a central role in conceptual change in the history of science (Kuhn, 1962), and many science educators have proposed using anomalous data to spur conceptual change in science students (e.g., Posner, Strike, Hewson, & Gertzog, 1982; Watson & Konicek, 1990). However, anomalous data frequently fail to promote conceptual change, because scientists and science students often find ways to discount the data in some way. For example, scientists may ignore or reject data that contradict their current theories, thus preserving their current theories from change. In order to understand the role of anomalous data in conceptual change, it is crucial to understand how people respond to anomalous data and why they respond as they do.

In order to understand the process of responding to anomalous data, one needs answers to two questions:

1. What are the different categories of response a person can make to anomalous data?
2. What are the factors that converge to produce each of the different responses? For example, what factors lead an individual to reject anomalous data in one instance but accept anomalous data in another instance?

In the remainder of this paper, I will address these two questions. My analyses are drawn from work done in collaboration with William Brewer. Further details can be found in Brewer and Chinn (1991) and in Chinn and Brewer (1992, 1993a, 1993b, 1993c).

In the first section of this paper, I present a taxonomy of seven forms of response to anomalous data. I present evidence for our taxonomy from the history of science and from our own program of experimental research. In the second section, I discuss factors that we have hypothesized will influence which of these seven responses an individual will choose.

SEVEN RESPONSES TO ANOMALOUS DATA

We conceptualize anomalous-data situation as follows: An individual currently holds Theory A. The individual then encounters data that appear to be inconsistent with Theory A. The anomalous data may or may not be accompanied by Theory B, which is intended to explain much of the domain of data explained by Theory A, plus the new anomalous data. We propose that there are seven ways in which a person can respond to the anomalous data. The person can:

1. ignore the data
2. reject the data
3. exclude the data from the domain of Theory A
4. hold the data in abeyance and retain Theory A
5. reinterpret the data and retain Theory A

6. reinterpret the data but make peripheral changes to Theory A
7. accept the data and change theories, perhaps adopting Theory B.

We believe that this is an exhaustive set of the psychologically plausible responses to anomalous data (see Chinn & Brewer, 1993a).

These seven responses vary along three dimensions, shown in Table 1. The first dimension is whether the individual accepts the anomalous data as valid. The second is whether the individual offers an explanation for why the data are accepted or not accepted. The third is whether the individual changes his or her theory in any way.

In the following section, I describe each of the seven responses, discussing their values on each of the three dimensions. I also briefly present examples of each response from the history of science and from our own program of experimental research (Chinn & Brewer, 1993c). Chinn and Brewer (1992, 1993a) have presented additional examples of these seven categories from the history of science, cognitive psychology, developmental psychology, social psychology, and science education.

1. Ignoring

An individual who ignores data does not believe that the data are valid, and the individual does not offer an explanation for why the data are invalid. Indeed, the individual gives no indication of having been exposed to the data. Theory A, of course, is not changed.

History of Science. According to Osborne (1979), the fact that hot water freezes faster than cold water was known to scientists through the writings of Aristotle, Descartes, and Bacon. But after the development of thermodynamics, this fact vanished from the scientific literature until it was rediscovered by a Tanzanian high school student.

Experimental evidence. In one series of experiments that we have conducted, undergraduates read about the theory that a meteor impact caused the mass extinctions at the end of the Cretaceous period. The undergraduates are provided with many lines of evidence supporting this theory, and after reading the evidence, most undergraduates report that they strongly believe the meteor theory. A key piece of evidence that they learn about is the fact that the KT boundary (the thin layer of clay that separates Cretaceous from Tertiary sediments) contains a very high concentration of the element iridium. Because iridium is extremely rare in the earth's crust but abundant in meteors, the high concentration of iridium suggests that a large meteor struck the earth. After reading about the meteor theory, the subjects next encounter a piece of anomalous data. For example, some subjects read about two independent lines of research supporting the conclusion that the KT boundary was deposited over 10,000 years or more. These data are anomalous for proponents of the meteor theory because the dust from a meteor impact would probably settle within a few months or years rather than over 10,000 years.

Some undergraduates have responded to this piece of anomalous data by rejecting one line of research supporting the conclusion that the KT boundary was deposited over 10,000 years while ignoring the other line of research. These subjects explain why they reject one line of research, but they do not even address the second, independent line of research. They appear to be totally ignoring the second line of research.

2. Rejection

Like an individual who ignores data, an individual who rejects data believes that the data are invalid. But unlike the individual who ignores data, the individual who rejects data does provide an explanation for why the data are invalid. Three common forms of rejection are rejection on the grounds of faulty methodology, rejection on the grounds that the data are merely random error, and rejection on the grounds that the data are fraudulent. An individual who rejects data makes no change at all to Theory A.

History of science. When Osborne assigned a laboratory assistant to carry out the first modern laboratory investigation of whether hot or cold water freezes faster, the assistant reported back that his data showed that hot water did freeze before cold water. He rejected his own data because of presumed methodological flaws. He promised, "We'll keep on repeating the experiment until we get the right result" (Mpemba and Osborne, 1969).

Experimental evidence. In our meteor theory experiments, more than half of the undergraduates who believe the meteor theory reject data that contradict the meteor theory. Some examples of their grounds for rejection are: "I'm skeptical of his methods of obtaining his theory," "Subtracting the year of the top and bottom rock doesn't seem to be a very accurate way of dating the [KT boundary]," and "It needs additional support from other scientists to support it."

3. Exclusion

Another response to anomalous data is to exclude the data from the domain of the current theory. In other words, the individual asserts that the data are irrelevant to Theory A, or that Theory A is simply not intended to account for these data (see Kuhn, 1962; Laudan, 1977). The person who excludes data from the domain of Theory A can either accept the anomalous data or remain agnostic about the validity of the data. Like the person who ignores data, the person who excludes data does not explain the data. And once again, there is no change in Theory A. Notice that individuals who exclude anomalous data are denying that the data are anomalous for Theory A.

History of science. One of the responses of professional paleontologists to the meteor theory of mass Cretaceous extinctions can be classified as exclusion. Although most scientists appear to have accepted that a large meteor struck the earth at the end of the Cretaceous period, many paleontologists have argued that a meteor strike, even if it occurred, is irrelevant to their theories of mass extinction. They maintain that the mass extinctions at the end of the Cretaceous were gradual, occurring over tens or hundreds of thousands of years. Therefore, they argue, the meteor impact, even if it occurred, is irrelevant to their theories of the mass extinctions (see Raup, 1986).

Experimental evidence. A few undergraduates in our meteor theory experiments give exclusion responses to anomalous data. They do not believe that the data are relevant to the meteor theory. For example, one subject wrote, "I didn't think this statement has much significance to dispelling the theory" and "I'm unsure as to the significance of the 10,000 yr old KT boundary."

4. Abeyance

Scientists frequently respond to anomalous data by holding the data in abeyance. An individual who holds data in abeyance cannot, at present, explain the anomalous data but is convinced that someone will eventually discover a way to explain the data within the current theoretical framework (see Kuhn, 1962). Abeyance is different from the previous forms of response in that the person accepts the anomalous data as valid data that Theory A should be able to explain. But the person cannot, at the present time, provide an explanation for the data. The individual does not change Theory A in any way because it is not yet clear how Theory A should be adjusted to explain the data.

History of science. When Ampère was developing his theory of electrodynamics, he was unable to explain one anomalous experiment that he himself had conducted. He held this anomaly in abeyance for over two years, until he was able to make a modification in his theory that could account for his data (Hofmann, 1988).

Experimental evidence. Some of the undergraduates in our meteor theory experiments hold the anomalous data in abeyance. These subjects report that they accept the validity of the data, but they refuse to reduce their belief in the meteor theory because the meteor theory has too much other evidence in its favor.

In another line of experiments that we have conducted (Brewer and Chinn, 1991), undergraduates have read about data that support several principles of quantum mechanics but violate certain fundamental beliefs held by most undergraduates. In response to the data, one student held the data supporting quantum mechanics in abeyance, arguing that physicists would eventually solve the paradoxes of quantum mechanics so that he would not need to give up his commitment to realism. In response to one question, he wrote, "Not sure--I'll tell you in 20 years," indicating his belief that scientists will eventually resolve the anomaly within his preferred realist framework.

5. Reinterpretation

This is the first response in which the individual both accepts the anomalous data as valid and explains the anomalous data. However, the individual does not need to change Theory A at all, because the individual claims that his or her current beliefs are perfectly adequate for explaining the data. Like individuals who exclude data from Theory A, individuals who reinterpret data are asserting that the supposedly anomalous data are not, in fact, anomalous for Theory A.

History of science. A good example of reinterpretation in the history of science is the case of the Piltdown skull, which was "discovered" in 1912 in England. The skull appeared to belong to an early hominid but was determined 40 years later to be a hoax. The discovery was anomalous because theories of the early development of hominids could not account for the presence of hominids in the British Isles. Soon after the original discovery, several scientists reinterpreted the discovery as a chance mixture of the skull of a human and the jaw of an ape rather than the skull and jaw of a hominid.

Experimental evidence. In our meteor theory experiments, some subjects who strongly believe the meteor theory reinterpret the anomalous data as being consistent with the meteor theory. For example, some subjects who are confronted with data supporting the conclusion that the KT boundary was deposited over 10,000 years argue that a meteor impact would produce so much dust that it is only natural to expect the dust to take 10,000 years or more to settle. For these subjects, the 10,000 year period is consistent with their intuitive models for what would happen if a large meteor hit the earth.

6. Peripheral theory change

Lakatos (1970) argued that a theorist can always protect core theoretical beliefs by changing less central, auxiliary hypotheses. We call such changes peripheral changes. When a person makes peripheral changes to Theory A in response to anomalous data, the individual accepts the data as valid and attempts to explain the data. However, the data can be explained only by modifying one or more relatively minor hypothesis in Theory A. In both reinterpretation and peripheral theory change, the individual believes that the anomalous data are generally consistent with Theory A. The difference is that with peripheral theory change, the individual cannot explain the data without making a minor change in the theory.

History of science. Both Scheiner and Galileo discovered what appeared to be spots on the sun. Scheiner, who wanted to preserve the immutability of the heavens, postulated that the "spots" were actually stars located between the earth and sun, whereas Galileo, who had no commitment to the Aristotelian world view, hypothesized that they were actual blemishes on the surface of the sun (Shea, 1970). If we assume that Scheiner had not believed that stars were located between the earth and sun prior to observing the spots, then his response to the spots is an example of peripheral theory change.

Experimental evidence. A few undergraduates in our meteor impact experiments have made peripheral theory changes to the meteor theory in response to anomalous data. One subject, for instance, attempted to account for the data purporting to show that the KT boundary had been deposited over 10,000 years by stating, "After the meteor impact there could have been widespread volcanic eruptions that spread the iridium over the earth." This subject accounted for the slow deposition of the KT boundary by adding the hypothesis that a meteor impact would trigger volcanic eruptions.

7. Theory change

A person may be so convinced by the anomalous data that he or she changes Theory A, perhaps adopting Theory B instead. In this case, the anomalous data are accepted, and they are explained, but they can be explained only by giving up core ideas from Theory A.

History of Science. A good example of rapid theory change in the history of science comes from Rutherford's theory of transmutation of elements. In the early years of this century, Soddy and Rutherford published data suggesting that elements undergo transmutation into other elements during radioactive processes. Although these data contradicted a long-entrenched belief among scientists that transmutation of elements was impossible, almost all scientists adopted the transmutation theory within a few years (Badash, 1966).

Experimental evidence. A very small number of subjects in the meteor theory experiments abandon the meteor theory following their encounter with anomalous data.

Summary

An individual can make any one of seven different response to anomalous data. Of the seven responses, only the last two involve any change in Theory A, and only the last produces a change that can be called theory change or conceptual change. The first six responses are <u>theory-preserving</u> responses, because the individual discounts the anomalous data in order to protect Theory A.

In the next section of this paper, I address a crucial issue in conceptual change: What causes people to respond to anomalous data as they do? For example, why does an individual reject data in one instance, reinterpret data in another instance, and change theories in yet another instance? I discuss a set of nine factors that influence how people respond to anomalous data.

FACTORS THAT INFLUENCE HOW PEOPLE RESPOND TO ANOMALOUS DATA

Chinn and Brewer (1993a) have proposed that an individual's response to anomalous data is determined by the convergence of four clusters of factors: (a) the individual's current beliefs, (b) the characteristics of the alternative theory, (c) the characteristics of the anomalous data, and (d) the individual's processing strategies. I will discuss nine specific factors across these clusters that we hypothesize will affect how people respond to anomalous data. These factors are not intended to be exhaustive; I present only those factors for there appears to be good evidence from psychology and education and from the history of science.

Characteristics of the Individual's Current Beliefs

Three characteristics of the individual's current beliefs appear to influence how the individual responds to anomalous data.

1. The entrenchment of Theory A. An entrenched theory is one that is deeply embedded in a network of explanatory beliefs. A theory can be entrenched for any of four reasons:

a. The theory is well-supported by evidence. For example, the common belief among chemistry students that matter is continuous seems firmly grounded in everyday observations of solid objects in the world.

b. The theory embodies central ontological assumptions, i.e., assumptions about the fundamental categories and properties of the world. When Theory A and Theory B differ in their ontological assumptions, theory change may be particularly difficult (see Chi, 1992). Brewer and Chinn (1991) found that undergraduates were unwilling to abandon their conventional assumptions about time and space when they were confronted with information about special relativity. Instead, most subjects rejected or reinterpreted the new information. Some subjects made peripheral changes to their beliefs, but none abandoned their original ontological assumptions.

c. The theory coheres with other explanatory theories. Among scientists the principle of the conservation of mass-energy is entrenched in part because it is used to support explanations in many different domains.

d. The theory satisfies social needs such as achieving desired goals, protecting one's ego, or preserving membership in a desired social group. For example, for proponents of creationism, an important source of entrenchment may be a desire to conform to the beliefs of fellow believers of creationism. It may be very difficult to overcome this social source of entrenchment with anomalous data alone.

When an individual holds a deeply entrenched theory, the individual is likely to make theory-preserving responses to the data and to avoid theory change. We have conducted two experiments designed to investigate this hypothesis. Both have used the experimental paradigm, described earlier, in which subjects learn about the meteor theory of Cretaceous extinctions and then encounter data anomalous for this theory. In two experiments, we have varied the amount of evidence that subjects receive in support of the meteor theory. Half of the subjects (the "entrenched" subjects) read a version of the meteor theory that provided extensive evidential support for the theory, including the information about the iridium in the KT boundary and information that the crater has been found. The other half of the subjects (the "nonentrenched" subjects) read a version that provided only one piece of evidence. Subjects next encountered anomalous data and an alternative theory, the theory that volcanic eruptions caused the dinosaur extinctions.

The results of these experiments indicated that entrenched subjects and nonentrenched subjects were equally likely to reject or reinterpret the anomalous data in the absence of an alternative theory. But nonentrenched subjects were much more likely than entrenched subjects to change theories once they learned about the alternative volcano theory. It appears that entrenched subjects were more likely than nonentrenched subjects to hold data in abeyance, whereas nonentrenched subjects were more likely to change theories.

2. Epistemological commitments. The term epistemological commitments refers to beliefs about what scientific knowledge is and how one should judge a scientific theory (cf. Posner et al., 1982). The available evidence suggests that children (and many nonscientist adults) possess sound commonsense epistemological principles but lack the more sophisticated epistemological commitments that have developed during the growth of science since the Renaissance.

In support of the notion that children possess sound commonsense epistemological commitments, Samarapungavan (1992) found that even children in the first grade prefer scientific explanations that are internally consistent and that are consistent with a broad range of evidence. However, other researchers have found that children, and often adults, lack more sophisticated epistemological understandings. For example, Carey et al. (1989) reported that many junior high school students do not fully understand the nature of scientific hypotheses and evidence. Additionally, many of these students believed that science advances by accumulating facts. Reif and Larkin (1991) have argued that scientists apply much higher standards of consistency than nonscientists do. It appears likely that epistemological shortcomings such as these impede theory change and promote theory-preserving responses. For example, individuals who do not insist that theories be rigorously consistent with empirical data may be more likely to ignore or exclude anomalous data or to hold the data in abeyance.

3. Background knowledge. When we use the term background knowledge, we are referring to scientific knowledge that a person uses to help evaluate data but that is not specifically part of the theory under evaluation. For example, a geologist possesses background knowledge about seismography, the physics of waves, and mathematics that is simply assumed to be true when investigating alternative models of the structure of the earth's core.

Background knowledge can trigger several different responses to anomalous data, depending on the particular interaction between background beliefs and the anomalous information. For instance, background beliefs about appropriate research procedures could compel acceptance of empirical data that adhered to those procedures but lead to rejection of data gathered by nonconventional techniques.

Interestingly, increased background knowledge about a particular scientific domain should increase the likelihood of reinterpretation. To reinterpret an experiment that contradicts a theory, an individual needs a store of ideas from which to draw possible reinterpretations. In one experiment that we have conducted, the number of university science courses taken by undergraduates was positively associated with the likelihood of reinterpreting information, but not with the likelihood of rejecting information. This suggests the possibility that a greater reservoir of specific scientific knowledge facilitates reinterpretation.

We have found that subjects in the meteor theory experiments typically appeal to extratheoretical background knowledge to justify their evaluations of anomalous data. In particular, subjects often appeal to beliefs they hold about appropriate methods for conducting experiments in geology. For example, one subject who rejected data wrote, "True timing is hard to predict in geological findings. There are so many environmental factors that were unknown." A subject who accepted data used this rationale: "a computer study and an actual lab study were highly correlational . . . . Also, the studies were done by 6 different labs in different countries."

Characteristics of the Alternative Theory

We propose that two characteristics of the alternative theory influence how people respond to anomalous data.

1. The availability of a plausible alternative theory. The history of science suggests that theory-preserving responses to anomalous data are more likely when there is no alternative theory or when the alternative theory lacks a plausible mechanism (Kuhn, 1962; also see Posner et al., 1982). Gould (1980, Ch. 19) provides an example. In Eastern Washington state there is a large area of volcanic basalt called the Scablands. Two regions within the Scablands are marked by numerous deep channels called coulees. Early in this century, the geologist Bretz hypothesized that the coulees had been caused by a vast catastrophic flood which carved the coulees within just a few days. Although Bretz accumulated a great deal of evidence for his hypothesis, other geologists rejected the idea that geological features had catastrophic origins. These geologists preferred to assume that the coulees were caused by many repeated floods over thousands of years. What Bretz lacked was a mechanism: he could not explain how so much water could be unleashed all at once. Other geologists accepted the catastrophic explanation only when a large glacial lake that had once existed in Montana was discovered; the evidence indicated that massive amounts of water from this lake had on several occasions gushed forth toward the west. This lake provided the mechanism that Bretz had lacked, and scientists then accepted Bretz's hypothesis. As Gould (1980) concludes, "Events that 'cannot happen' according to received wisdom rarely gain respectability by a simple accumulation of evidence for their occurrence; they require a mechanism to explain how they can happen" (p. 167).

Evidence from psychology and education also suggests that theory change is more likely when an alternative theory with a plausible mechanism is available (see Chinn & Brewer, 1993a). People find it difficult to discover new alternative theories on their own, and in the absence of an alternative theory, they often cling to their previous theory (e.g., Burbules & Linn, 1988). And even when an alternative theory is present, people are likely to reject it if there does not appear to be a plausible mechanism. A good example comes from a study of classroom instruction in electricity by Johsua and Dupin (1987). Students in the classrooms studied by Johsua and Dupin believed that current "wears out" as it travels around a simple circuit. That is, the students did not believe that current is the same everywhere in a circuit; instead, some current gets used up as it passes through light bulbs and wires. The students resisted even very strong evidence showing that the current was constant. The reason for their resistance was that they had no mechanism that could explain how the battery could wear out and yet maintain a constant current. They believed that the only way to account for the battery wearing out was to assume that some current was lost as it went around the circuit. It was only when the teacher used an analogy to explain how the battery could maintain constant current while gradually losing energy that the students accepted the constant-current hypothesis. This analogy convinced the students that the constant-current hypothesis was supported by a plausible mechanism.

2. The quality of the alternative theory. Recent research in cognitive and developmental psychology suggests that people are more likely to change theories when the alternative theory is "better" than the current theory in the senses that (a) the alternative theory explains a wider scope of evidence than the current theory, (b) the alternative theory is more accurate than the current theory, and (c) the alternative theory is internally consistent. Samarapungavan (1992) found that first graders preferred theories that met these three criteria. Chinn and Brewer (1992; also Schank & Ranney, 1991) found that undergraduates were more likely to change their theories in response to anomalous data when the alternative theory covered a wider scope of data more accurately.

The intelligibility of the alternative theory. Posner et al. (1982) have argued that conceptual change is more likely when the alternative theory is intelligible. There is some evidence, however, that students sometimes adopt theories that they understand poorly (Linn & Songer, 1991); therefore, more research on this topic appears to be needed.

Characteristics of the Anomalous Data

We hypothesize that three aspects of the anomalous data influence how people respond to the data.

1. Credibility of the data. Individuals will reject data that are not credible. Credible data are likely to preclude ignoring or rejection, and they may promote theory change. However, even when data are credible, an individual may preserve the current theory by choosing responses of exclusion, abeyance, reinterpretation, or peripheral theory change. We hypothesize that there are five ways to make data more credible.

a. Enhance the reputation of the experimenter. Anecdotes from the history of science suggest that a researcher's credibility influences whether fellow scientists believe the data collected by the researcher. For example, after Röntgen reported the discovery of X rays, one fellow physicist wrote, "I could not help thinking that I was reading a fairy tale, though the name of the author and his sound proofs soon relieved me of any such delusion" (Glasser, 1934, p. 29). Social psychologists have found that messages presented by credible sources are more believable than messages presented by noncredible sources (see Reinard, 1988).

b. Replicate the data. In our meteor theory experiments, we have presented some subjects with anomalous data consisting of a single experiment conducted by a single scientist. Subjects sometimes reject these data on the grounds that replication is needed. We have recently obtained data that suggests that some subjects are more likely to believe anomalous data when they believe that the experiments used to generate the data have been replicated.

c. Adhere to accepted data-collection methods. For clinical trials of new medicines to gain widespread acceptance in the medical research community, the trials must adhere to the accepted double-blind methodology.

d. Allow people to observe data directly. Those who believe in UFOs and alien abductions would no doubt find it easier to convince skeptics if they could produce an actual flying saucer or an alien for scientists to examine directly. Science teachers follow a similar intuition when they conduct classroom demonstrations instead of merely telling students what the results of an experiment would be.

e. Use data that people already know about and believe. For example, one way to counter the common belief that the first of two lights in a series in an electrical circuit will be brighter than the second might be to ask students whether lights in a string of Christmas tree lights vary in brightness (cf. Heller & Finley, 1992).

2. Ambiguity of the data. Ambiguous data are data that can be explained equally well by rival theories. For example, the observable movement of the sun in the sky is completely ambiguous with respect to heliocentric and geocentric theories of the motion of the earth and the sun (cf. Hanson, 1958). The motion is equally well explained by assuming that the sun is moving or by assuming that the earth is rotating. Ambiguous data are easy for rival theories to reinterpret, each within their own framework.

It is probably true that <u>all</u> data are ambiguous. However, we believe that some data are relatively unambiguous and hard to reinterpret. An example comes from the history of the interpretation of dinosaur tracks (see Desmond, 1975). The tracks of small bipedal dinosaurs are similar to those of birds; hence, scientists often argued that these were bird tracks. However, it was harder to reinterpret the data of larger tracks, and so some scientists accepted the larger tracks as dinosaur tracks before those from small dinosaurs.

Research reported by Stavy (1991) indicates that unambiguous data are more likely to promote theory change in the classroom than are ambiguous data. In her study, some students observed an experiment in which acetone, which is colorless, was boiled. Despite a demonstration that the boiled acetone weighed the same as the liquid acetone, the students resisted the conclusion that mass was conserved during the boiling. Other students were shown blue iodine being boiled; these students could clearly see blue gas remaining in the flask. These students were much more likely to accept the idea that mass is conserved. The blue iodine gas presented students with a relatively unambiguous demonstration that the iodine did not simply disappear, and these students were more likely to change theories.

3. Existence of multiple lines of evidence. In science, it usually requires many studies, often spanning years of research, to rule out all possible grounds for rejecting or reinterpreting a piece of anomalous data. Many examples from the history of science and from science education suggest that numerous pieces of data can converge to produce theory change instead of theory-preserving responses to anomalous data. In recent experiments, we have found that students are more likely to accept data when the data are supported by replicated studies representing independent lines of evidence (Chinn & Brewer, 1993c).

Processing Strategies

We find evidence for one processing strategy that influences how people respond to anomalous data.

1. Deep processing. Research by social psychologists indicates that when people process anomalous data deeply (i.e., consider the data carefully), they are more likely to change their theory in response to the data (see Chinn & Brewer, 1993a). One powerful method for promoting deep processing in individuals is to tell the individuals that they will have to justify their evaluations of the data to others (Chaiken, 1980). Having students debate alternative explanations for a piece of data also appears to promote deep processing of data (e.g., Johsua & Dupin, 1987).

SUMMARY AND COMMENT

Understanding how people respond to anomalous data appears to be crucial to understanding conceptual change. People can respond to anomalous data in any of seven different ways: ignoring, rejection, exclusion, abeyance, reinterpretation, peripheral theory change, or theory change. I have discussed nine factors that are hypothesized to influence which of these seven responses people, including science students, will choose in a particular situation.

One goal of science education is to promote theory change. The framework presented in this paper can help educators understand how to make theory change more likely in response to anomalous data. Teachers can promote theory change by orchestrating the factors that influence how students respond to anomalous data so as to maximize the likelihood of theory change.

However, theory change is not the only goal of science education. A second goal of science education is to promote reflective consideration of evidence. It is often more rational to discount a piece of data than to accept it and change theories. Using the framework presented here, teachers can help students learn what the possible responses to anomalous data are and which responses are most rational in different situations.

REFERENCES

Badash, L. (1966, August). How the "newer alchemy" was received. Scientific American, pp. 88-95.

Brewer, W. F., & Chinn, C. A. (1991). Entrenched beliefs, inconsistent information, and knowledge change. In Proceedings of the 1991 International Conference of the Learning Sciences (pp. 67-73). Charlottesville, VA: Association for the Advancement of Computing in Education.

Burbules, N. C., & Linn, M. C. (1988). Response to contradiction: Scientific reasoning during adolescence. Journal of Educational Psychology, 80, 67-75.

Carey, S., Evans, R., Honda, M., Jay, E., & Unger, C. (1989). 'An experiment is when you try it and see if it works': A study of grade 7 students' understanding of the construction of scientific knowledge. International Journal of Science Education, 11, 514-529.

Chaiken, S. (1980). Heuristic versus systematic information processing and the use of source versus message cues in persuasion. Journal of Personality and Social Psychology, 39, 752-766.

Chi, M. T. H. (1992). Conceptual change within and across ontological categories: Implications for learning and discovery in science. In R. Giere (Ed.), Minnesota Studies in the Philosophy of Science: Vol. XV. Cognitive models of science (pp. 129-186). Minneapolis, MN: University of Minnesota Press.

Chinn, C. A., & Brewer, W. F. (1992). Psychological responses to anomalous data. Proceedings of the Fourteenth Annual Conference of the Cognitive Science Society (pp. 165-170). Hillsdale, NJ: Erlbaum.

Chinn, C. A., & Brewer, W. F. (1993a). The role of anomalous data in knowledge acquisition: A theoretical framework and implications for science instruction. Review of Educational Research, 63, 1-49.

Chinn, C. A., & Brewer, W. F. (1993b). Factors that influence how people respond to anomalous data. Proceedings of the Fifteenth Annual Conference of the Cognitive Science Society (pp. 318-323). Hillsdale, NJ: Erlbaum.

Chinn, C. A., & Brewer, W. F. (1993c). Responding to anomalous scientific data: Effects of entrenchment, background knowledge, strength of data, and an alternative theory. Manuscript in preparation.

Desmond, A. J. (1975). The hot-blooded dinosaurs: A revolution in paleontology. New York: Dial.

Driver, R., Guesne E., & Tiberghien, A. (1985). Children's ideas in science. Milton Keynes, England: Open University Press.

Glasser, O. (1934). Wilhelm Conrad Röntgen and the early history of the Roentgen rays. Springfield, IL: Charles C. Thomas.

Gould, S. J. (1980). The panda's thumb: More reflections in natural history. Harmondsworth, Middlesex, England: Penguin Books.

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

Heller, P. M., & Finley, F. N. (1992). Variable uses of alternative conceptions: A case study in current electricity. Journal of Research in Science Teaching, 29, 259-275.

Hofmann, J. R. (1988). Ampère's electrodynamics and the acceptability of guiding assumptions. In A. Donovan, L. Laudan, and R. Laudan (eds.), Scrutinizing science: Empirical studies of scientific change (pp. 201-217). Dordrecht: Kluwer Academic Publishers.

Kuhn, T. S. (1962). The structure of scientific revolutions. Chicago: University of Chicago Press.

Johsua, S., & Dupin, J. J. (1987). Taking into account student conceptions in instructional strategy: An example in physics. Cognition and Instruction, 4, 117-135.

Lakatos, I. (1970). Falsification and the methodology of scientific research programmes. In I. Lakatos and A. Musgrave (eds.), Criticism and the growth of knowledge (pp. 91-196). London: Cambridge University Press.

Laudan, L. (1977). Progress and its problems. Berkeley: University of California Press.

Linn, M. C., & Songer, N. B. (1991). Teaching thermodynamics to middle school students: What are appropriate cognitive demands? Journal of Research in Science Teaching, 28, 885-918.

Mpemba, E. G., & Osborne, D. G. (1969). Cool? Physics Education, 4, 172-175.

Mulkay, M., & Gilbert, G. N. (1982). Accounting for error: How scientists construct their social world when they account for correct and incorrect belief. Sociology, 16, 165-183.

Osborne, D. G. (1979). Mind on ice. Physics Education, 14, 414-417.

Posner, G. J., Strike, K. A., Hewson, P. W., & Gertzog, W. A. (1982). Accommodation of a scientific conception: Toward a theory of conceptual change. Science Education, 66, 211-227.

Raup, D. M. (1986). The Nemesis Affair: A story of the death of dinosaurs and the ways of science. New York: W. W. Norton & Company.

Reif, F., & Larkin, J. H. (1991). Cognition in scientific and everyday domains: Comparison and learning implications. Journal of Research in Science Teaching, 28, 733-760.

Reinard, J. C. (1988). The empirical study of the persuasive effects of evidence: The status after fifty years of research. Human Communication Research, 15, 3-59.

Samarapungavan, A. (1992). Children's judgments in theory choice tasks: Scientific rationality in childhood. Cognition, 45, 1-32.

Schank, P., & Ranney, M. (1991). Modeling an experimental study of explanatory coherence. In Proceedings of the Thirteenth Annual Conference of the Cognitive Science Society (pp. 892-897). Hillsdale, NJ: Erlbaum.

Shea, W. R. (1970). Galileo, Scheiner, and the interpretation of sunspots. Isis, 61, 498-519.

Stavy, R. (1991). Using analogy to overcome misconceptions about conservation of matter. Journal of Research in Science Teaching, 28, 305-313.

Thagard, P. (1992). Conceptual Revolutions. Princeton, NJ: Princeton University Press.

Watson, B., & Konicek, R. (1990). Teaching for conceptual change: Confronting children's experience. Phi Delta Kappan, 71, 680-685.

Table 1
Seven Responses to Anomalous Data

	Dimensions of the Response		
Response	Whether the data are accepted as valid	Whether the data are explained	Whether Theory A is changed
Ignoring	no	no	no
Rejection	no	yes	no
Exclusion	yes or maybe	no	no
Abeyance	yes	not now, but it will be possible to do so later	no
Reinterpretation	yes	yes	no
Peripheral change	yes	yes	yes, but only peripheral beliefs are changed
Theory change	yes	yes	yes, core beliefs are changed