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Abstract

A crucial aspect of understanding knowledge acquisition and theory change is understanding how people respond to anomalous information. We propose that there are seven fundamental responses that people make to anomalous information. We provide evidence from the history of science and from psychology for each of these responses, and we present the results of a study that explores some of the factors that determine these responses.

Anomalies play a pivotal role in the process of knowledge change. On the one hand, anomalous data can force the learner to realize that a current theory must be changed because it is inconsistent with the real world. On the other hand, people often distort or explain away anomalous data so as to protect their favored theories. Thus, the process of theory change appears to be mediated by the way in which a person evaluates anomalous data. In order to understand the process of theory change, we need a more complete understanding of *how* people respond to anomalous data and *why* they respond as they do.

The disciplines that have been most interested in theory change have not provided detailed accounts of people's response to anomalous data. In artificial intelligence, for example, anomalous data are usually treated as correct and unimpeachable (Tweney, 1990). Most scientific discovery and theory revision systems assume that any empirical data that conflict with the current theory are correct; it is the theory that must be changed (e.g., O'Rorke, Morris, & Schulenburg, 1989; Rajamoney, 1989).

In cognitive and developmental psychology, there is widespread recognition that people often discount anomalous data in some way (e.g., Dunbar, 1989; Kuhn, 1989; Piaget, 1980). However, there has been little work on analyzing the specific ways in which people discount anomalous data. Nor has there been a systematic attempt to delineate the factors that affect the way people respond to anomalous data.

The history and philosophy of science contain many insights relevant to the process of responding to anomalous data (Kuhn, 1962; Lakatos, 1970; Laudan, 1977). However, most of these insights are asides given in the course of analyzing particular cases in the history of science.

We propose that 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, we will address these two questions. In the first section, we present a classification of seven forms of response to anomalous data. We present evidence for our classification from the history of science and from psychology. In the second section, we discuss factors that we hypothesize will influence how people respond to anomalous data, and we present the results of an experiment designed to test our hypotheses.

Responses to Anomalous Data

Suppose that a person holding theory A encounters anomalous data that is inconsistent with theory A. The anomalous data may be accompanied by an alternative theory B, which is a competitor of theory A.

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, or (7) accept the data and change theory A, perhaps adopting theory B. We think that this is close to an exhaustive set of the possible responses to anomalous data.

These seven responses vary along three dimensions. The first dimension is whether the individual accepts the anomalous data as valid. The second is whether the individual offers an explanation for why he or she has accepted or not accepted the data. And the third is whether the individual changes his or her theory in any way. As we present each of the seven responses, we will discuss their values for each of the three dimensions. We will also briefly present evidence from the history of science and from empirical studies in psychology for the validity of each form of response.

1. Ignoring

A person who ignores data does not accept the data as valid. No explanation for the data is offered, nor is theory A changed at all. The person gives no indication of having been exposed to the data.

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.

Psychology. The typical psychology experiment is designed so as to make ignoring contradictory data very difficult for the subject. There are a few studies that state that subjects appear to be ignoring anomalous data (e.g., Klahr & Dunbar, 1988), but the experimental situations do not provide enough information for us to be sure these data fit our criteria for ignoring.

2. Rejection

Like a person who ignores data, the person who rejects data does not accept the data as valid. But unlike the person who ignores data, the person who rejects data does generate an explanation for why the data are invalid. This explanation can range from a detailed critique of experimental methodology to a vague claim that something must be wrong with the experiment. With rejection, there is no change at all in theory A.

History of science. In the dispute between Millikan and Ehrenhaft over the nature of charge on the electron, each rejected the other's data on methodological grounds (see Holton, 1978). Ehrenhaft believed that Millikan had illegitimately discarded data in order to support his view that electron charge was unitary. Millikan's rejoinder was to argue that Ehrenhaft was mixing bad data with good data in order to achieve results that appeared to support the case against unitary charge.

Psychology. Champagne, Gunstone, and Klopfer (1985) report a study in which students who believed that heavy objects fall faster than light objects subsequently watched the teacher attempt to refute their beliefs by dropping two blocks of different weights from a common height. Although the blocks appeared to strike the ground simultaneously, two middle school students "reasoned that the blocks had, in fact, fallen at different rates, but that the difference in descent times was too small to be observed over the short distance (approximately one meter) used in the original demonstration" (p. 65). These students rejected the experiment as methodologically too insensitive to detect the predicted effect.

3. Exclusion

Another response to anomalous data is to assert that the data are not relevant to theory A, i.e., that theory A is not intended to account for this 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 offer any account of the data. And once again, there is no change in theory A.

History of science. According to Laudan (1977), most theorists in the nineteenth century excluded Brownian motion from their theories. At various times, Brownian motion was regarded as a biological problem, as a chemical problem, as a problem of electrical conductivity, and as a problem in heat theory. "So long as the problem remained unsolved, any theorist could conveniently choose to ignore it simply by saying that it was not a problem which theories in *his* field had to address" (Laudan, 1977, pp. 19-20, italics in original).

Psychology. Karmiloff-Smith and Inhelder (1975; Karmiloff-Smith, 1988) investigated children attempting to balance blocks on a narrow metal support. Some of the blocks were ordinary blocks that balanced at their geometric centers, but other blocks had a weight hidden at one end so that they did not balance at their geometric center. Some children developed the theory that things balance in the middle, but with this theory they couldn't get the weighted blocks to balance. Instead of changing their theory, these children declared that the uneven blocks were impossible to balance and did not worry about them further, which suggests that the children excluded the data from their theory. Their theory was intended to cover only normal blocks, and they felt no need to develop a theory that encompassed all of the blocks.

4. Abeyance

A common response to anomaly is to hold it in abeyance. In this case, the individual faced with anomalous data cannot explain the data but is confident that it will eventually be given an account within the theoretical current framework (Kuhn, 1962). Abeyance is different from the previous forms of response in that the person accepts the anomaly as valid data that his or her theory should be able to explain. But the person cannot, at the present time, provide an explanation for the data.
History of science. An example of abeyance comes from Ampère's assessment of contrary evidence during the period when he was developing his theory of electrodynamics. Ampère was unable to explain one anomalous experiment that he himself had conducted. This anomaly was held 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).
Psychology. Brewer and Chinn (1991) had undergraduate subjects read about experiments supporting several principles of quantum mechanics. These principles violated certain deeply-entrenched beliefs held by most of the subjects. In response to the data, one subject held the data in abeyance, confident 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 the realist framework.

5. Reinterpretation

When a person reinterprets anomalous data, he or she accepts the data as valid, at least at some level. The person also offers an explanation to account for the data, but the explanation is such that the person need not change theory A at all. In effect, the person acknowledges the data but claims to be able to explain them without altering theory A at all.
History of science. When Alvarez proposed the meteor impact theory of Cretaceous extinctions, his main evidence was an anomalously high concentration of iridium in the K-T boundary (the clay separating the Cretaceous and Tertiary sediments). Some scientists reinterpreted the iridium anomaly as normal seepage of trace amounts of iridium from layers of limestone above the K-T boundary (Raup, 1986). These scientists did not deny the iridium anomaly, but they reinterpreted it as having a terrestrial source rather than an extraterrestrial source.
Psychology. Piaget (1980, Chapter 6) asked children to predict what would happen when equal weights were put in each pan of a balance scale. Most young children predicted that one pan would go down and the other up, like a seesaw. After watching the experimenter place one weight in each pan and finding that nothing happened, a six year old hesitated and scrutinized the scale closely. Then the child declared that the pans were in the same place because both weights were light. The child did not reject the data; there was no attempt to deny that the pans were level. But the data were reinterpreted to show that it was only because the weights were too light that the seesaw effect did not occur.

6. Peripheral theory change

Lakatos (1970) argued that a theorist can always preserve favorite hypotheses in a theory by changing less central, auxiliary hypotheses. When a person makes a 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 hypothesis in theory A.
History of science. Galileo's critics denied that there were mountains on the moon because they believed the moon was a perfect sphere. When one of Galileo's opponents looked through Galileo's telescope, he conceded that he saw mountains, but he declared that the mountains were embedded in a perfectly transparent crystal sphere (Drake, 1980). In this way, he protected his core belief that the moon was a

perfect sphere by adding an additional hypothesis.

Psychology. Vosniadou and Brewer (in press) have found that most young children (ages 4-6 years) have a flat earth theory of the shape of the earth. When young children are told by adults that "the earth is round," they are faced with anomalous data. Some of the children account for this anomalous data by making peripheral changes in their flat earth view. For example, some children interpret the data from the adults to indicate that the earth is a flat disc. This approach accounts for the anomalous data about the earth being round but leaves the basic flat earth belief intact.

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 are explained only by giving up core ideas from theory A.

History of Science. The chemical revolution is a good example of theory change. Driven by more than a decade of active empirical research, much of which was anomalous for the phlogiston theory, almost all chemists abandoned phlogiston theory in favor of Lavoisier's oxygen theory (Musgrave, 1976).

Psychology. Even those psychological experiments that demonstrate that many people distort and discredit data also find that some people do change their theories. For example, in the Karmiloff-Smith and Inhelder (1975) research, older children eventually do use the anomalies to develop an improved theory of balancing.

Factors that Influence How People Respond to Anomalous Data

From the point of view of understanding the process of theory change, the crucial question is why a person chooses one response over another. We have begun a series of studies designed to answer this question, and we will present some preliminary data in the present paper.

In the study reported here, we chose two factors that the literature suggested might be particularly powerful influences on how people respond to anomalous data. The first factor is how entrenched a person's beliefs are. An entrenched belief is a belief that has a great deal of evidentiary support and participates in a broad range of explanations in different sub-domains. The more entrenched a belief is, the more it should resist change, and the more likely it should be that anomalous data will be ignored, rejected, excluded, held in abeyance, or reinterpreted.

The second factor is specific background knowledge related to the anomalous data. We hypothesize that the availability of pertinent background knowledge should strongly influence the likelihood of rejection or reinterpretation. For example, background knowledge or beliefs about proper procedures for conducting experiments should lead a person to accept data that has been gathered according to those procedures but to reject data that has not been gathered according to those procedures. In the present study, we decided to focus on background knowledge that might raise the likelihood of rejecting or reinterpreting data.

Method

Domain. The domain in this study was the mass extinction at the end of the Cretaceous period.

Subjects. The subjects were 54 undergraduates enrolled in an introductory psychology course at the University of Illinois at Urbana-Champaign.

Design. Degree of entrenchment and type of background knowledge were manipulated in a 2 X 3 factorial design. There were two levels of entrenchment: entrenched versus non-entrenched. There were three levels of background knowledge: provision of background knowledge for rejecting anomalous data, provision of background knowledge for reinterpreting the anomalous data, and provision of no background knowledge.

Procedure. Each subject began by reading a version of the meteor impact theory. Subjects in the entrenched condition read a 5-page text containing a broad array of evidence supporting the theory. The evidence included the iridium anomaly in the K-T boundary, the discovery of a crater that is the appropriate size and age, anomalous isotope ratios, and several other pieces of evidence. Subjects in the non-entrenched condition read only about the iridium anomaly.

Embedded in one third of these texts was a piece of background knowledge that could be used to reject anomalous data that would be encountered later (e.g., some texts asserted that small-scale laboratory models of global events are not very reliable). Embedded in another third of the texts was a piece of background knowledge that could be used to reinterpret anomalous data that would be encountered later (e.g., some texts explained different ways in which some species might survive 18 months of darkness). The remaining third of the texts contained no background information that could be used to reject or reinterpret the anomalous data.

After reading these texts, subjects rated their belief in the impact theory on a 0 to 10 Likert scale. Then they were provided with a piece of contradictory evidence (e.g., some students read that based on extrapolations from a small-scale laboratory model, a scientist had concluded that a meteor striking the earth would produce so much dust and debris that all sunlight would be blocked for 18 months, effectively killing all life; the scientist argued that since we know that all life was not exterminated, a meteor could not have struck the earth). Subjects rated their belief in this evidence and wrote an explanation for their rating. They re-rated their belief in the impact theory, explaining any change in their belief.

Then all subjects read a brief description of an alternative theory that explains the iridium anomaly by positing that a prolonged period of intense volcanic activity on earth caused the iridium anomaly as well as the extinctions (iridium is also contained in some volcanic magma). Then subjects rated their belief in the volcano theory and the impact theory, explaining their ratings.

Finally, the subjects were provided with a second piece of evidence that contradicted the impact theory (and supported the volcano theory). Subjects rated their belief in the evidence, in the impact theory, and in the volcano theory, again explaining their beliefs and any changes.

Results and Discussion

Effects of entrenchment. Entrenchment clearly influenced whether subjects changed theories. Subjects in the entrenched condition firmly maintained their belief in the meteor theory. Even after being presented with two pieces of contradictory evidence and a plausible alternative theory, entrenched subjects' mean belief in the meteor impact theory was much stronger than their mean belief in the volcano theory (7.2 versus 4.3). This positive difference was significant [$t(24) = 4.61$, $p < .001$]. By contrast, after being presented with the two pieces of contradictory evidence and the volcano theory, non-entrenched subjects preferred the volcano theory. Mean belief in the meteor impact theory was only 4.5, while mean belief in the volcano theory was 6.1 [$t(21) = -2.56$, $p < .05$].

Thus, our manipulation of entrenchment clearly affected subjects' belief in the alternative theories.

Table 1
Effects of Entrenchment
on Responses to the Evidence:
Frequency and Percentage of Each Response

	Entrenched		Non-Entrenched	
Ignoring	0	(0%)	0	(0%)
Rejection	27	(57%)	25	(54%)
Abeyance	3	(6%)	1	(2%)
Exclusion	0	(0%)	0	(0%)
Reinterpretation	6	(13%)	2	(4%)
Theory change	11	(23%)	18	(39%)

There was also an indication that entrenchment affected the distribution of responses to anomalous data. Table 1 presents the distribution of responses to the two pieces of evidence in the entrenched and non-entrenched conditions. The pattern was not as pronounced as we had expected.

Effects of background knowledge. Our manipulation of background knowledge failed to influence the likelihood that subjects would reject or reinterpret data. Only two subjects whose texts included experimentally-provided information that could be used to reject the anomalous data used that information as grounds for rejecting data. Similarly, only two subjects who read texts that provided information that could be used to reinterpret the anomalous data used that information to reinterpret the data.

The reason for the subjects' failure to use the background information provided in the text appears to be that they instead used background knowledge that they brought with them to the experiment. For example, some subjects used their background knowledge about experimentation and about the physical world to reject the data that declared that a meteor would kill everything because it would block all sunlight for 18 months: "The earth is much too big and different to be correctly represented by some small rock in a laboratory. Things like atmosphere, spin, gravity, etc. play a part as well." Others used their background knowledge not to reject the claim that the earth would be dark for 18 months but to reinterpret it to show that all life would not be killed: "<u>Some</u> things could survive with no light, for example, anaerobic respirators." Others appeared to rely on background intuitions to ratify the study's conclusions: "I think he knows what he's talking about. If a large meteor did hit the earth, a lot of debris would be thrown in the air."

It appears, then, that background knowledge is very important in the response to anomalous data. But it may be difficult for background knowledge supplied by the text to compete with background knowledge already possessed by students. The background knowledge in the text may be less accessible than students' own prior knowledge. (The alert reader will note that this paragraph is an example of reinterpretation on our part!)

Summary and Conclusions

We have argued that understanding how people respond to anomalous data is crucial to understanding the process of knowledge change. We have proposed a taxonomy of seven forms of response to anomalous data, and we believe that this taxonomy can provide a framework for systematic investigation into the factors that influence how people respond to anomalous data. In the study reported here, we found that the entrenchment of beliefs and the availability of background knowledge influenced how undergraduates responded to anomalous data.

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