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Authors
Chinn, Clark A.
Brewer, William F.

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Clark A. Chinn
Center for the Study of Reading
University of Illinois at Urbana-Champaign
51 Gerty Drive, Champaign IL 61820
chinn@vmd.cso.uiuc.edu

William F. Brewer
Department of Psychology
University of Illinois at Urbana-Champaign
603 East Daniel, Champaign IL 61820
wbrewer@s.psych.uiuc.edu

Abstract

In order to understand conceptual change, it is crucial to understand how people respond to anomalous information. 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, we present a taxonomy of seven responses to anomalous data. Second, we present an analysis of eight factors that are hypothesized to influence which of these seven responses an individual will choose. Finally, we present the results of an experiment that investigates several of these eight factors.

A key to understanding conceptual change is understanding how people respond to anomalous information. Information that contradicts an individual's current beliefs is important because without it, an individual has no need to alter current conceptions. Without the goad of anomalous information, current conceptions are perfectly adequate for understanding the world.

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 in science education (Chinn & Brewer, in press). Moreover, most artificial intelligence systems that model scientific discovery and theory change use anomalous data to trigger the theory change process (e.g., Kulkarni & Simon, 1988).

Chinn and Brewer (1992, in press) have proposed a detailed taxonomy of possible responses to anomalous data. When an individual who holds theory A encounters anomalous data, which may be accompanied by an alternative theory B, the individual can choose one of seven responses to the anomalous data:

1. *Ignore* the data.
2. *Reject* the data because of methodological flaws, random error, or alleged fraud.
3. *Exclude* the data from the domain of theory A by asserting that theory A is not intended to explain th data.
4. Hold the data in *abeyance*, i.e., concede tha theory A cannot explain the data at present but asser that theory A will be elaborated in the future so tha it can explain the data.
5. Accept but *reinterpret* the data so as to make th data consistent with theory A.
6. Accept the data and make minor, *periphera changes* to theory A.
7. Accept the data and *change theories*, possibly t theory B.

Of these seven responses, only the last two involv any change in theory A, and only the last produces change that can be called conceptual change. Th first six responses are *theory-preserving* response because the individual discounts the anomalous dat in order to protect theory A.

In this paper, we address a crucial issue in con ceptual change: What causes people to respond t anomalous data as they do? For example, why doe an individual reject data in one instance, reinterpre data in another instance, and change theories in ye another instance? We propose a set of eight factor that influence how people respond to anomalous data then we report the results of an experiment designe to investigate several of these factors.

Factors that Influence How People Respond to Anomalous Data

We propose that an individual's response to anoma lous data is determined by the convergence of thre clusters of factors: (a) the individual's current belief (b) the characteristics of the alternative theory B, an (c) the characteristics of the anomalous data. We wi discuss specific factors in each of these clusters tha we hypothesize will affect how people respond t anomalous data. These factors are not intended to be exhaustive; we present only those factors for which we think there is good evidence from psychology and from the history of science.

Characteristics of the Individual's Current Beliefs

We postulate that three characteristics of the individuals' current beliefs 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 because it is well-supported by evidence, because it embodies central ontological assumptions, because it coheres with other explanatory theories, or because it satisfies social needs such as protecting one's ego (see Chinn & Brewer, in press). 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.

Chinn and Brewer (1992) found evidence that theories that are entrenched because of strong evidential support promote theory-preserving responses to anomalous data. Undergraduates read about the theory that the mass extinctions at the end of the Cretaceous period were caused by a meteor striking the earth. Half of the subjects read a version that provided extensive evidential support for the theory; the other half read a version that provided only one piece of evidence. Subjects next encountered two pieces of anomalous data and an alternative theory. Subjects who had received the well-supported version of the meteor impact theory were less likely to change theories than subjects who had received the poorly-supported version.

2. Epistemological commitments. By epistemological commitments, we mean beliefs about what scientific knowledge is and how one should judge a scientific theory. 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 relationship between scientific hypotheses and evidence. Additionally, many of these students believe 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, a failure to insist that theories be rigorously consistent with empirical data could lead individuals to ignore or exclude anomalous data or to hold the data in abeyance.

3. Background knowledge. The term *background knowledge* refers to scientific knowledge that enters into data evaluation but that is not specifically part of the theory under evaluation. For example, an astronomer possesses background knowledge about chemical spectra that are simply assumed to be true when investigating alternative theories about galactic motion.

Background knowledge is a double-edged sword; it can promote either theory-preserving responses or theory change, depending on the 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.

Chinn and Brewer (1992) found that undergraduates invoked a wide range of background knowledge when they evaluated anomalous data and that they tended to rely on their own prior background knowledge instead of on information contained in a newly read text.

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 indicates that scientists frequently make theory-preserving responses to anomalous data when no plausible alternative theory is available (cf. Kuhn, 1962). An example is described by Gould (1980, Ch. 19). Eastern Washington state is dominated by an area of volcanic basalt called the Scablands. In two areas of the Scablands, there are many deep channels called coulees. After World War I, Bretz hypothesized that the channels were the work of a vast catastrophic flood which swept the plains and gouged out the channels within just a few days. This hypothesis flew in the face of the prevailing belief that all geological formations were the product of gradual change. Despite accumulating evidence marshaled by Bretz, geologists of the time preferred to assume that the channels 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. The geology community became convinced that a more catastrophic explanation was needed only when geologists in Montana found evidence that a large glacial lake that once existed there had poured out massive amounts of water to the west.

In an experimental study, Burbules and Linn (1988) examined the effects of anomalous data on adolescents' knowledge about how much water is displaced by heavier-than-water objects of different sizes, shapes, and weights. The students began with the misconception that the weight of an object determines how much water is displaced. A period of experimentation led many students to the correct principle, but many other students persisted in their original theory. However, once these students were told the correct principle, they changed their theory. Anomalous data were not sufficient to cause students to abandon their theory; a plausible alternative theory was needed to trigger theory change.

2. The quality of the alternative theory. Good evidence exists 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 and (b) the alternative theory is more accurate than the current theory. Samarapungavan (1992) found that first graders preferred theories that met these two criteria. Chinn and Brewer (1992) found that subjects were more likely to change their theories in response to anomalous data when the alternative theory covered a wider scope of data more accurately.

Characteristics of the Anomalous Data

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

1. Credibility of the data. Individuals will reject data that are not credible. Data that are credible may produce the responses of exclusion, abeyance, reinterpretation, peripheral theory change, or theory change, but not rejection.

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).

It seems reasonable to suppose that the credibility of data can be enhanced by enhancing the reputation of the experimenter, by adhering to accepted data-collection methods, by replicating the data, and by allowing people to observe experimental results directly. Clear psychological support exists for the first of these. Social psychologists have found that messages presented by credible sources are more believable than messages presented by noncredible sources (see Reinard, 1988).

2. Ambiguity of the data. Individuals can readily reinterpret data that are ambiguous with respect to two rival theories. Although it is probably true that it is possible to reinterpret any anomalous data, we believe that some data can be 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 these were accepted as dinosaur tracks before those from small dinosaurs.

Research reported by Stavy (1991) indicates that unambiguous data are more likely to promote theory change than are ambiguous data. In her study, students who observed an experiment in which acetone, which is colorless, was boiled resisted the conclusion that mass was conserved during the boiling. However, students who observed blue iodine being boiled could clearly see blue gas remaining in the flask. Confronted with a relatively unambiguous demonstration that the iodine did not simply disappear, these students accepted the notion that mass is conserved.

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 line 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 (see Chinn & Brewer, in press). There is little empirical research on this issue, however.

Experiment

This experiment was designed to investigate how the following factors influence the response of individuals to anomalous data: (a) possession of an alternative theory, (b) the strength of the data, (c) current theoretical commitments, and (d) background knowledge.

Method

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

Subjects. The subjects were 64 undergraduates enrolled in an introductory educational psychology course.

Design. Two factors, the availability of an alternative theory (available versus not available) and the strength of the data (strong versus weak), were manipulated in a 2 X 2 design. Pilot work had led us to doubt whether manipulation of the strength of the data would produce reliable effects because subjects can draw upon background knowledge to find ways to discredit almost any data, but we hoped that manipulating the strength of the data would increase the range of qualitative responses made to the data.

Procedure and materials. All subjects began by reading a 1600-word text about the meteor impact theory of Cretaceous extinctions; seven separate pieces of evidence in support of the theory were presented. One piece of evidence, for example, was that the layer of clay that marks the end of Cretaceous sediments in the geologic record throughout the world contains an extremely large amount of iridium. The text explained that meteors were the most plausible source of such a high concentration of iridium. After reading about the theory, subjects rated their belief in the meteor impact theory. This rating, like all other ratings described below, was made on a 0 to 10 Likert scale. Subjects also wrote down an explanation for each rating they made. Subjects in the alternative-theory condition then read about an alternative theory stating that the mass extinctions were caused by prolonged, massive volcanic eruptions. These subjects then rated their belief in both theories. Subjects in the no-alternative-theory condition did not receive any information about the volcano theory.

Next all subjects read about a piece of data that was anomalous for the meteor impact theory. Subjects in the weak-data condition were given the results of a single scientific experiment but were told little about the method of the experiment. There were two different pieces of weak data, counterbalanced across subjects in the weak-data condition. As an example, one piece of weak data stated that two scientists had examined the layer of clay at one site and had concluded that it had been deposited over 10,000 years, not over a few months or years as the meteor impact theory suggests. Subjects in the strong-data condition received one of two counterbalanced pieces of strong data. The two pieces of strong data were generated on the basis of responses made by pilot subjects to the two pieces of weak data; we attempted to create data that would meet all of the objections raised by these earlier subjects to the weak data. For example, one piece of strong data explained that numerous scientists all over the world using two independent methods had all concluded that the clay boundary had been deposited over 10,000 years.

After reading the data, subjects rated the data in two different ways. First, they rated the extent to which they believed that the data were valid. This provided a measure of whether the subjects accepted or rejected the data. Second, they rated the extent to which they believed that the data (if valid) were *inconsistent* with the meteor impact theory. This was a measure of whether the subjects reinterpreted the data; a low score on this scale indicated that the subject was reinterpreting the data as consistent with the meteor impact theory. Then subjects rated and explained their current belief in the meteor impact theory again. Subjects in the alternative-theory condition also rated and explained their belief in the volcano theory a second time.

Results and Discussion

Effects of the alternative theory. Surprisingly, the alternative theory affected neither the evaluation of data nor the later ratings of the meteor impact theory. For instance, there was no difference between alternative-theory subjects and no-alternative-theory subjects in the decrease in ratings given the meteor impact theory after exposure to the anomalous data [decreases of .97 and .72, respectively, $F(1,63) < 1$]. A possible explanation for this result is that the lack of an alternative theory produces theory-preserving responses only when subjects have a strong need for a theory to explain a domain of data. Most undergraduates probably do not feel a pressing need to have a theory to explain Cretaceous extinctions. Perhaps in domains where people really need a viable theory, they will not give up their theory until an alternative is available.

Effects of strength of data. Consistent with our earlier pilot data, the manipulation of the strength of the data did not influence subjects' ratings of the data (e.g., ratings of belief: 5.4 versus 5.6, $F < 1$). An examination of the written protocols suggested that some subjects were influenced by the strong data. Other subjects were able to discount the strong data only by ignoring one of the two independent lines of evidence presented; 7 of the 16 subjects who rejected the strong data did so by attacking one of the lines of research but ignoring the other.

Effects of theory preference on data evaluation. We carried out a series of follow-up analyses by dividing the subjects into two groups. One group, the volcano proponents, included the ten subjects in the alternative-theory condition who preferred the volcano theory immediately before reading the anomalous data. The other group, the meteor impact theory proponents, included the 32 subjects in either the alternative-theory or the no-alternative-theory condition who gave the meteor impact theory a high belief rating (8 or higher) immediately before reading the anomalous data.

There was a strong effect of theory preference on how subjects rated the data. Proponents of the volcano theory rated the *exact same data* as more believable than did proponents of the meteor impact theory [7.2 versus 5.1, $t(40) = 2.48$, $p < .02$]. Moreover, proponents of the volcano theory were much more likely than proponents of the meteor impact theory to accept the data. Accepting the data was defined as *both* believing that the data were valid (i.e., giving the data a belief rating of 6 or more) *and* believing that the data were inconsistent with the meteor impact theory (i.e., giving the data an inconsistency rating of 6 or more). By this definition, 6 of the 10 volcano proponents accepted the data; only 4 of 32 meteor impact proponents accepted the data. This difference was statistically reliable [$\chi^2(1) = 7.04$, $p < .01$]. The remaining 28 meteor impact proponents rejected the data, reinterpreted the data, or did both.

These results indicate that the subjects' theoretical commitments exerted very strong effects on their evaluation of the same piece of data. The size of this effect was unexpected. Considering that the subjects were unlikely to have been deeply or emotionally committed to the meteor impact theory, it is surprising that they were so strongly resistant to accepting the anomalous data. Subjects' evaluation of data was heavily theory-laden.

Anomalous data as mediating belief change. The results also suggest that subjects' ratings of data were not entirely theory-laden. Some subjects did accept the data despite a strong belief in the meteor impact theory, and when subjects accepted the data, they also lowered their belief in the meteor impact theory.

We did not expect either subjects' ratings of whether they believed the data or their ratings of whether the data were inconsistent with the meteor impact theory to be reliably associated with belief change. This is because data given high belief ratings can be discounted by giving the data low inconsistency ratings, and *vice versa*. Thus, it is necessary to have a measure that indicates the extent to which subjects discounted the data either by rejection or reinterpretation. An appropriate measure is obtained by multiplying the belief measure with the inconsistency measure (cf. Carlson & Dulany, 1988). A high score on this multiplicative measure indicates that a subject both believe the data and views the data as inconsistent with the meteor impact theory. A score near zero is obtained when either belief or inconsistency ratings are near zero.

Belief change was not reliably associated either with subjects' ratings of whether they believed the data ($r = -.24$) or with subjects' ratings of whether the data were inconsistent with the meteor impact theory ($r = -.27$). However, the multiplicative measure was reliably associated with belief change ($r = -.46$, two-tailed $p < .001$). A regression analysis showed that controlling for all manipulated factors and for prior belief in the meteor impact theory, the multiplicative measure of discounting data was strongly related to belief change [$F(1,63) = 23.66$, $\Delta R^2 = .25$). Thus, even when top-down theory-laden effects were statistically controlled, subjects' evaluation of the data independently influenced later belief. Subjects who fully accepted the data decreased their belief in the meteor impact theory more than subjects who discounted the data via rejection or reinterpretation.

Background knowledge. Given the massive discounting of the data by the subjects who preferred the meteor impact theory, it is important to examine their rationale for discounting the data. We have therefore carried out a qualitative examination of the explanations provided by the subjects.

Summary of reasons for rejecting data. In all, 33 subjects provided classifiable explanations for why they rejected the first piece of anomalous data. Their explanations fell into five categories: (a) rejection because the scientists had overlooked one or more relevant experimental factors, (b) rejection because of specific methodological flaws, (c) rejection on the grounds that more research or more information was needed, (d) rejection on the grounds that the meteor-impact theory was so well-supported that the new data must be incorrect, and (e) rejection because the data contradicted some nontheoretical or nonmethodological background beliefs, such as beliefs about other empirical data that would be hard to explain if the anomalous data were valid.

Summary of reasons for accepting data. Reasons for accepting data as valid fit into comparable categories: (a) acceptance because of good methodology, (b) acceptance because of multiple replications or independent lines of evidence, (c) acceptance because of the general prestige of science and scientists, (d) theory-driven acceptance, and (e) acceptance because of consistency with nontheoretical background knowledge and intuitions. The protocols

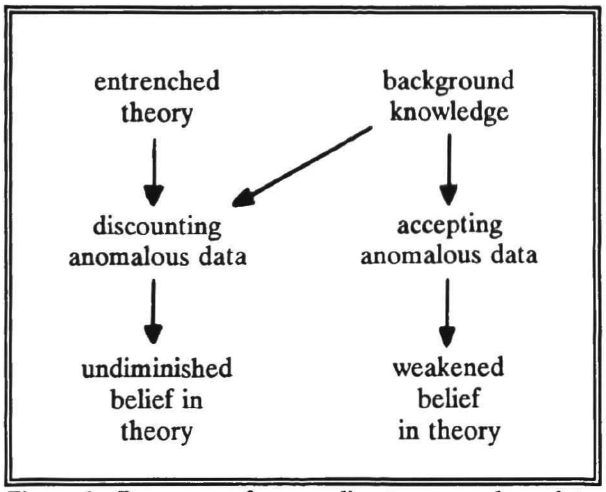

Figure 1. Processes of responding to anomalous data.

suggest that those subjects who believed the meteor impact theory but nevertheless accepted the data did so because their background knowledge told them that the data were valid, often because of specific methodological strengths.

General Discussion

The data reported in this paper suggest that subjects responded to anomalous data in the manner shown in Figure 1. The strongest influence on how subjects processed anomalous data was their theoretical commitment. Subjects who strongly believed the meteor impact theory tended to discount the data and thereby maintain their belief in the meteor impact theory. Most of these subjects also appealed to extra-theoretical background knowledge to justify their discounting of the data. By contrast, it appears that some subjects' background knowledge constrained them to accept the anomalous data. When this occurred, their acceptance of the data further constrained them to reduce their belief in the current theory. A continuing sequence of anomalous data, then, might eventually lead to abandonment of the current theory in favor of an alternative theory.

The crucial link in the theory change process is the link between background knowledge and accepting the anomalous data. In our experiment, only a few subjects who strongly believed the meteor impact theory accepted the anomalous data. The design of the present experiment does not allow us to answer the question of how these individuals differed from those who did not accept the anomalous data. Resolution of this important issue awaits future research.

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