Title
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Which Parts of Scientific Explanations are Most Important?

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Abstract

Given the depth and breadth of available information, determining which components of an explanation are most important is a crucial process for simplifying learning. Two experiments tested whether people believe that components of an explanation with more elaboration are more important. In Experiment 1, participants gave higher importance scores for components that they judged to be elaborated upon by many other components. In Experiment 2, the amount and type of elaboration was experimentally manipulated. Experiment 2 demonstrated that elaboration increases the importance of the elaborated information by providing insight into understanding the elaborated information; information that was too technical to provide insight into the elaborated component did not increase the importance of the elaborated component. While learning an explanation, people piece together the structure of elaboration relationships between components and use the insight provided by elaboration to identify important components.

Keywords: Explanation; Science Education; Summarization

Introduction

A hallmark of modern culture is dramatically increased access to information. People are often confronted with an overwhelming depth and breadth of information for a given explanation. For example, consider how many pieces of information you have amassed from different sources about global warming. Is it most important to focus on carbon dioxide emissions from humans, sun spots, the ice-albedo positive feedback loop, methane release from peat bogs, or deforestation, etc? In order to limit our search for useful information and decide which information to try to understand and remember, we must focus on the most important components of explanations. Indeed, when learning a textual passage, people focus on the information they judge to be important, which leads to selectively better recall (e.g., Brown & Smiley, 1978; Johnson, 1970).

What determines which components people think are most important? One common theoretical position is that information high up in a hierarchical structure of a text represents the most important information (e.g., Thorndyke, 1977). One modern approach from computational linguistics (Marcu, 1999) suggests that important components of a text can be identified by the discourse structure and the rhetorical relations in the text. For example, consider a text about Mars presented by Marcu; "With its distant orbit … and slim atmospheric blanket, Mars experiences frigid weather conditions." Marcu argues that the first half of the sentence "with... blanket" is subordinate to the second half "Mars ... conditions." The second half expresses what is more essential to the writer's purpose and is comprehensible independently of the first half, making it more important. In fact, Marcu found that his algorithm based on which components *rely upon others for comprehension* predicts peoples' judgments of which components are important for including in a summary.

Extrapolating Marcu's (1999) hypothesis about text to explanations, it seems likely that people view components of explanations that are *independently comprehensible* to be more important than components that are incomprehensible without first knowing the independent component. For example, one must understand the basic concept of global warming (the average temperature of the earth is increasing) before understanding how greenhouse gasses contribute to global warming. Here we say that a component of an explanation, Y, "elaborates" on X when Y provides additional details about X and X must be understood first in order to understand Y. In our studies, we assess whether people identify important components of explanations as those that have the most elaboration – i.e., the most components that depend upon it in order to be understood.

The current experiments investigated which components of large scientific explanations people think are most important. Instead of judging importance based on a textual explanation of the sort one might read in an encyclopedia, we were interested in situations when a person learns many facts and develops an explanation by combining the different pieces of knowledge. For example, a person might accumulate bits of related knowledge over time from multiple sources including testimony, direct experience, or even through induction and deduction. When devising an explanation, a person must sort through all this information and decide what is most important. Such a process may occur constantly in our daily experiences as we update our explanatory interpretations of the world, discarding unimportant information and retaining central concepts.

Investigating how people identify important information in *unstructured explanations* is essential for two reasons. First, much of the previous work on importance has focused on intact text which contains many cues to importance (e.g,, topic sentences and conclusions and how sentences are ordered within paragraphs). Studying unstructured explanations can help us isolate structural and content factors that people use to identify import components from purely textual factors. Second, much of the previous research has focused on how people identify important parts of stories. However, narrative stories often follow one individual character on a temporal journey, and much of the work has focused on "story grammar" categories such as settings, goals, and internal responses (e.g., Omanson, 1982; van den Broek, 1988), making it unclear how importance in stories would translate to explanations. In contrast, explanations have richer, more interconnected, and less linear structures compared to stories (Keil, 2006).

In the present experiments, we ask whether people use elaboration relationships to determine the important parts of an explanation, even when presented in fragments. In Experiment 1, we examined whether elaboration relations between components predict which components people think are important. In Experiments 2, we experimentally manipulated the amount and type of elaboration to examine why elaboration influences perceived importance.

Experiment 1

The purpose of Experiment 1 was to investigate whether components of an explanation that are elaborated by many other components are generally judged to be more important. To this end, participants rated the importance of components and drew graphs showing which components they thought elaborated upon which other components.

Method

Participants Sixteen Yale students participated either for course credit or pay at a rate of $10 per hour.

Materials Four explanations (Diabetes, GPS, Fiber Optics, and the Circadian Rhythm) were written to meet the following criteria. No indicator phrases (e.g., "the main point," "it is critical to know that") were included. Thus, participants could not rely upon surface features of the text to determine which pieces of information were most important but instead had to understand the content.

Furthermore, the explanations were broken up into components (between 17 and 26 per explanation) and presented to participants on individual cards (M=26 words per card, SD=12; see Figure 1). Breaking up the text simulated how people learn in the real world by aggregating and combining information from multiple different sources to develop a unified explanation. This method also eliminated cues to importance present in intact texts such as topic sentences and conclusions and the order of sentences.

The text on each card was constructed so that it could be understood individually; however, textual components naturally refer to concepts introduced on other cards. Thus, some cards are not understandable without first understanding another card. In these cases the dependent card adds more information that is relevant to the independent card. We call this "elaborating." The cards used for the Circadian Rhythm explanation appear in Figure 1.

Procedure Due to time limitations, half of the participants worked with the Diabetes and GPS explanations, and the other half worked with the Circadian Rhythm and Fiber Optics Explanations. Participants were first given a set of cards and told that the cards together comprise an explanation for how a scientific phenomenon (e.g., diabetes) works. Participants were asked to read the cards thoroughly until they felt satisfied that they understood the explanation inherent in the cards. Participants were told that the order of the cards was random, that they might need to read the cards repeatedly for the cards to make sense, and that they were allowed to spread out the cards on a desk to read simultaneously. In fact, the cards were randomly sorted like shuffling a deck of cards for each participant.

After reading the first set of cards, participants answered the following question: "How important for understanding how the phenomenon works is this card compared to the other cards?" Participants rated each card on a scale from one (not important) to nine (extremely important). Participants then performed the same tasks on a second set of cards pertaining to another phenomenon. The order in which they worked with the two explanations was counterbalanced between participants.

After rating the importance of the cards in both explanations, participants read the following instructions explaining how to draw graphs (e.g., Figure 1) depicting which cards elaborated on which other cards: "In general, some cards are elaborated by many other cards. Cards with lots of elaboration go at the top. The cards that elaborate upon them go underneath them with arrows pointing downwards to the cards that elaborate upon the cards above. Cards that are elaborated less, or not at all, get placed near the bottom…." Elaboration was left undefined so that participants would use their intuitive notion of elaboration.

Results

Consensus Graphs Figure 1 presents the consensus elaboration graph produced by participants for Fiber Optics as well as the average importance rating for each card. Consensus elaboration graphs were created for visualization purposes to understand the stimuli and task and display the elaboration relationships between cards that participants most frequently endorsed. The consensus graphs were not involved in the formal analyses. A given elaboration relationship between two cards (an arrow) was included in the consensus graph if at least 3 out of 8 participants endorsed the particular relationship. At this cutoff, almost all the cards were linked with at least one other card. These graphs informally confirm the hypothesis that cards with more elaboration are more important. Cards near the top of Figure 1 with many elaborating cards generally have higher importance ratings than cards near the bottom of the graph with fewer elaborating cards.

Formal Analyses The purpose of Experiment 1 was to determine whether elaboration predicts importance ratings. We first accomplished this goal by comparing all the pairs of cards for which a participant said that one card directly elaborated upon the other. For example, in Figure 1, the top card "A circadian rhythm is a roughly-24-hour cycle…" is directly elaborated upon by "Circadian Rhythms are important for…." On average, elaborated cards were significantly more important than elaborating cards (Mdifference=.88, SD=.53), $t(15)=6.56$, $p<.01$.

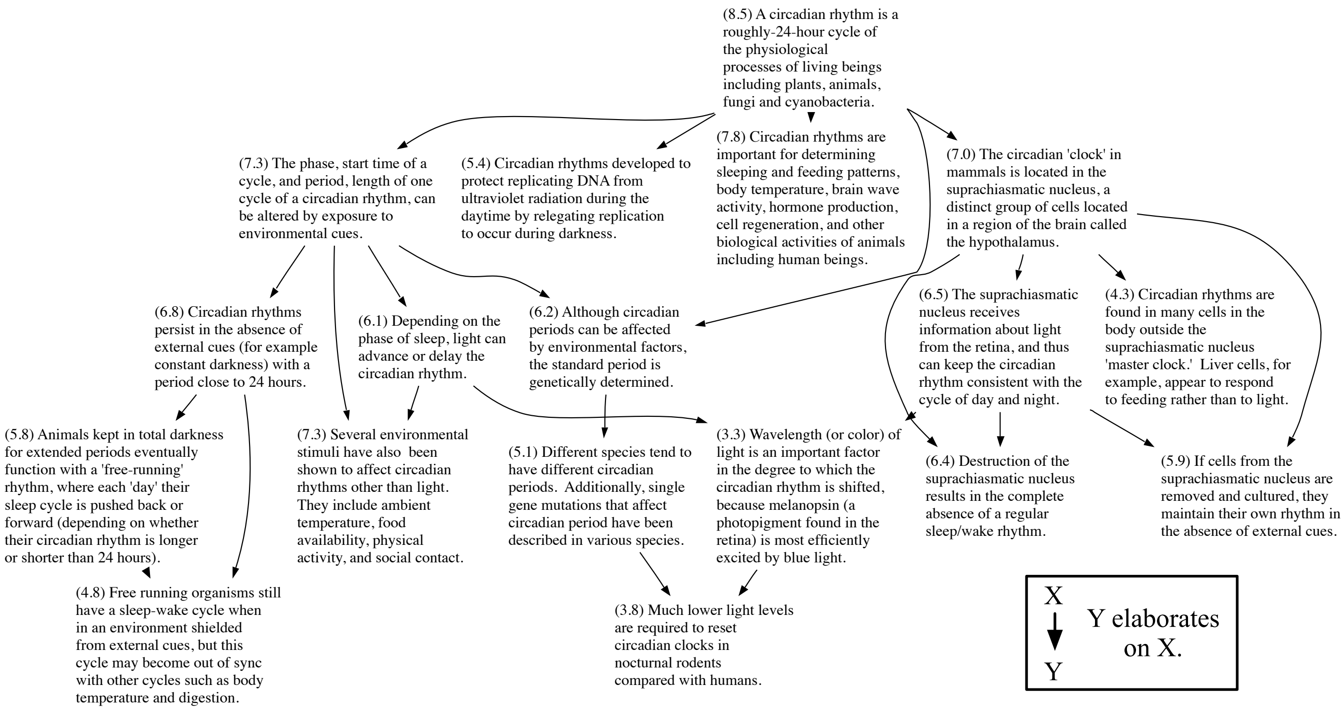

Figure 1: Consensus Elaboration Graph for the Circadian Rhythm Explanation in Experiment 1.
Note: Numbers represent average importance rating for a given card.

We also examined whether elaboration relations predicted the overall importance of a card. We compared two different metrics that capture different aspects of the elaboration relationships. The "amount of elaboration" metric was defined as the number of cards that could be reached by traversing down the elaboration graph, including the card itself. For example, the card at the bottom of Figure 1 starting with "Much lower light…" gets an elaboration score of 1, the card on the left starting with "Circadian rhythms persist…" gets a score of 3, and the card at the top starting with "A circadian rhythm is a roughly…" gets a score of 18 because all the cards elaborate upon it. This metric reflects the idea that a component of an explanation is important to the extent that many other cards directly or indirectly depend on it to be comprehendible. We compared this metric to another metric that just captures the number of direct relationships or associations with other cards. For example, the card starting with "Much lower light levels…" participates in two elaboration relationships whereas "Circadian rhythms persist…" participates in three and "A circadian rhythm is …" participates in 5.

For each of the two explanations that a participant worked with, we computed Spearman Rank Order correlations between the participant's importance scores and the scores of the two metrics, producing four correlations per participant. We then averaged the two correlations that involved the same metric by Fisher-transforming the correlation coefficients, producing two correlation coefficients per participant. (The means below represent these average correlation coefficients that were inversely transformed to lie on a scale of 0-1.) On average, the "total amount of elaboration" metric predicted participants' responses fairly well (M=.42, SD=.07), and significantly above chance, $t(15)=6.74$, $p<.01$. Though the "number of relations" metric (M=.26, SD=.05) was also above chance, $t(15)=5.00$, $p<.01$, it was significantly worse at predicting participants' importance ratings, $t(15)=5.68$, $p<.01$.

In sum, this experiment demonstrated that people piece together components of explanations to understand the structure of the elaboration relationships between components. Furthermore, the more elaboration a component has, the more important people consider it to be for understanding the entire explanation.

Experiment 2

We sought to answer two remaining questions with Experiment 2. First, so far we have argued that people use elaboration to identify important components in an explanation. However, because there was not any experimental manipulation of elaboration in Experiment 1, a third factor could conceivably cause both increased elaboration as well as importance. For example, it is possible that the cards that were elaborated on were also inherently important independent of elaborations. Additionally, some have argued that people can identify important sentences merely based on sentential features such as sentence length and number of pronouns used and that identifying such sentences does not depend upon the sentences' relationships to other sentences (McCarthy et al., 2008). In Experiment 2, we manipulated whether a card was elaborated or not to determine whether, in fact, elaboration influences which components people judge to be important,

Table 1: One Circadian Rhythm Key Card and Elaborations in Experiment 2.

Key Card: The circadian "clock" in mammals is located in the suprachiasmatic nucleus, a distinct group of cells located in a region of the brain called the hypothalamus.		
Mechanistic Elaborating Cards:	**Historical Elaborating Cards:**	**Too Technical Elaborating Cards:**
The suprachiasmatic nucleus receives information about light from the retina, and thus can keep the circadian rhythm consistent with the cycle of day and night. The process of aligning the cycle of the suprachiasmatic nucleus with the cycle of day and night is called "entrainment."	The discovery that the suprachiasmatic nucleus represents a major circadian pacemaker occurred simultaneously in two laboratories, one headed by Robert Y. Moore (then at the University of Chicago) and the other headed by Irving Zucker at the University of California, Berkeley.	The suprachiasmatic nucleus is situated in the anterior part of the hypothalamus, immediately dorsal and superior to the optic chiasm and bilateral to the third ventricle. The suprachiasmatic nucleus sends information to other hypothalamic nuclei and the pineal gland to regulate body temperature and production of cortisol and melatonin.
If cells from the suprachiasmatic nucleus are removed from the brain and cultured, they maintain their own rhythm in the absence of external cues. This shows that the suprachiasmatic nucleus can serve as an autonomous clock.	To celebrate the 25th anniversary of the discovery of the suprachiasmatic nucleus as the circadian clock, Charles A. Czeisler and Steven M. Reppert organized a meeting at Harvard Medical School in 1997.	Neurons in the ventrolateral suprachiasmatic nucleus have the ability for light-induced gene expression. Melanopsin-containing ganglion cells in the retina have a direct connection to the ventrolateral suprachiasmatic nucleus via the retinohypothalamic tract.
Destruction of the suprachiasmatic nucleus results in the complete absence of a regular sleep/wake rhythm.	Though Irving Zucker contributed to the discovery of the suprachiasmatic nucleus, his advisor Robert Moore, suggested that Zucker leave graduate school. Moore later recanted.	The surachiasmatic nucleus is composed of densely packed, parvocellular neurons and is nearly always identifiable by cytoarchitectonic criteria.
Circadian rhythms are found in many cells in the body outside of the suprachiasmatic nucleus "master clock." Liver cells, for example, appear to respond to feeding rather than light.	One of the first major papers on the role of the suprachiasmatic nucleus was submitted to the journal Science, but rejected, and later published in a lower-tier journal.	One division of the suprachiasmatic nucleus has a large population of vasoactive intestinal polypeptide-containing neurons. The second division is characterized by a population of vasopressin-containing neurons.

above and beyond any third factors.

A second question is why elaboration affects the importance of elaborated information. Normally, an explainer would elaborate on a component to provide insight into or clarity about the elaborated component. For example, "The circadian "clock" in mammals is located in the suprachiasmatic nucleus…" is elaborated by "The suprachiasmatic nucleus receives information about light from the retina, and thus can keep the circadian rhythm consistent with the cycle of day and night." The elaborating card explains a critical function of the suprachiasmatic nucleus. Thus, it makes sense that the elaborating card would make the elaborated card more important.

In order to test whether elaboration increases the importance of the elaborated information by providing insight into the elaborated information, we manipulated the content of the elaboration (see Table 1). "Mechanistic" elaborations explained details of how the elaborated information works and thus provide insight into the elaborated information. (By "mechanistic" we do not intend to exclude other causal information such as a function or non-causal information such as temporal sequences, parts of a whole, subtypes, or mathematical algorithms. All of these can further explain how something works.) *"Too technical"* elaborations referred to concepts in the elaborating cards, but used terminology that was likely far beyond the comprehension level of a non-specialist and would not actually provide the novice reader with any better understanding of how the phenomenon works. Thus, the too technical elaborations test whether information needs to *personally add to the comprehension of the phenomenon*, in order to affect the importance of the elaborated component. Finally, people might use a simple pragmatic rule that "important components of explanations are more frequently elaborated than unimportant components." In order to test this possibility, we tested *"historical"* or sociological elaborations that did not provide insight or clarity into how these biological and technological phenomena work. In sum, if providing insight into the elaborated component is necessary for elaboration to increase the importance of the elaborated component, then only the mechanistic elaboration would suffice.

It is important to note that this elaboration manipulation was fairly subtle. As demonstrated in Experiment 1, all or almost all of the components in an explanation engage in elaboration relationships, and the cards that were added to provide additional elaboration in this experiment and the cards that were elaborated upon were simply part of this larger structure of elaboration relationships between components. The elaborated and elaborating cards were treated exactly the same as all the other cards and were not in any way identified as being the subject of investigation.

Method

Participants There were 36 participants from the same population.

Materials The explanations were similar to those in Experiments 1, but were modified in one critical way. In each explanation, four “key” cards were chosen, each of which could be elaborated upon. For each of these four key cards, 12 elaborating cards were created, four elaborating cards of each of the three types (mechanistic, historical, and too technical). Sample stimuli for one circadian rhythm key card and its elaborating cards appear in Table 1. (Note that the circadian rhythm explanation contained three other key cards and associated elaborations, as well and other cards presented to all participants like the cards in Figure 1.) For a given key card, the three types of elaborating cards had the same total word length. For example in Table 1, each of the three sets of elaborating cards has a total word length of 125. This insured that no type of elaboration was generally longer than another across participants.

Procedure Participants were randomly assigned to one of four conditions. Participants worked with all four explanations in one of four counterbalanced orders such that each explanation was first for some participants. For each explanation, participants thoroughly read the cards until they felt that they understood the explanation, and then rated all the cards for importance (same as in Experiment 1). For a given participant and a particular explanation, one key card was elaborated upon by four mechanistic cards, a second key card was elaborated by four historical cards, a third by four too technical cards, and the fourth was not elaborated upon. The pairing of a key card with the types of elaboration was counter-balanced between subjects. The elaborating cards and the key cards were treated just like all the other cards and were not identified as the subject of investigation in any way.

To ensure that participants actually thought that the elaborating cards elaborated upon the key cards as intended, a separate groups of 16 participants read the same explanations as the main group of participants and drew elaboration graphs of all the cards including the key cards and elaborating cards (see Experiment 1 for the instructions for drawing the elaboration graphs).

Results

The main results were that only the mechanistic elaborations increased the importance of the key cards. Additionally, degree of importance of the mechanistic elaborations per se strongly predicted the importance of their key cards, but this relationship was much weaker for the other elaborations.

Manipulation Checks We performed a manipulation check to ensure that participants actually thought that the elaborating cards elaborated on the key cards as intended, and that this was true for the historical and too technical elaborations to the same degree as the mechanistic elaborations. To assess this, we looked at the separate group of participants' elaboration graphs. For each explanation with which a participant worked, there were four cards of each of the three elaboration types. From participants' elaboration graphs, we took the average of the number of elaboration cards that participants thought directly or indirectly elaborated upon the intended key card per elaboration type and per explanation (4 is the maximum). Participants thought that most of the elaborating cards did elaborate on the intended key cards; (M=3.13, SD=0.71) for mechanistic elaborations, (M=3.19, SD=1.24) for historical explanations, and (M=3.28, SD=0.69) for too technical elaborations. A one-way repeated-measures ANOVA did not find a main effect of explanation type, $F(2,30)<1$. This ensures that any differences between the elaborated cards due to the type of elaboration are not the product of participants' failing to recognize the elaboration relationships for these cards.

We also analyzed the importance of the elaborating cards per se. As a baseline, the mechanistic elaborations were generally viewed as somewhat important (M=5.78, SD=1.2). The historical elaborations were intended to not actually facilitate understand how the phenomena work. As expected, these cards were rated as fairly unimportant (M=2.00, SD=0.78), and significantly less important than the mechanistic cards $t(35)=18.37$, $p<.01$. We were not entirely sure whether the too technical cards would be viewed as important or not. If participants had extensive knowledge of the phenomena and could understand these cards, they would be viewed as important, but even if participants did not understand these cards, they still might be viewed as potentially important. That is, it is obvious that they do explain the science behind the phenomena, but they likely would not contribute to the average readers' comprehension. The too technical cards were viewed as somewhat important (M=4.29, SD=1.08), less important than the mechanistic cards, $t(35)=6.36$, $p<.01$, but more important than the historical cards, $t(35)=11.63$, $p<.01$.

Elaborated Cards The main question was whether the different types of elaborations increased the importance of the elaborated key cards. Each participant worked with four explanations, and within each explanation there was one key card elaborated by each of the four types of elaboration. Within a participant, we collapsed across the four explanations. The key cards with mechanistic elaborations were rated as more important (M=6.97. SD=1.29) than those with historical elaborations (M=6.37, SD=1.31), $t(35)=3.22$, $p<.01$, too technical elaborations (M=6.52, SD=1.32), $t(35)=2.82$, $p<.01$, and no elaboration (M=6.49, SD=1.39), $t(35)=2.61$, $p=.01$. Furthermore, the key cards with historical elaborations, and too technical elaborations, were not judged to be any more important than the key cards with no elaboration, $ts(35)<1$.

Relationship Between Elaborated and Elaborating Cards Did the degree to which participants viewed the elaborating cards to be important per se predict the degree to which they judged the key cards to be important? For each of the four explanations, and each of the three types of elaborations, we computed correlations between the average importance score of the four elaborating cards and the importance score of the elaborated key card. Averaged across the four explanations, the importance scores of the mechanistic elaborations strongly predicted the importance of their key cards (r=.61, p<.01). The importance of the historical elaborations did not predict the importance of their key cards (r=.14, p=.21), and those of the too technical elaborations weakly predicted the importance of their key cards (r=.28, p=.05). Furthermore, the correlations were significantly stronger for the mechanistic cards than the historical cards, Z=2.30, p=.02, and marginally stronger for the mechanistic cards than the too complex cards, Z=1.71, p=.08, non-directional. It should be noted, however, that these findings do not necessarily imply that the importance of the elaboration causes the importance of the key cards to increase. It is possible that when a key card is viewed as important, its elaborations are also viewed as important. The findings do suggest a tight connection between the importance of the key cards and mechanistic elaborations.

General Discussion

Two experiments demonstrated that the amount of elaboration of a component of an explanation predicts its importance. Experiment 1 found that components tended to be rated as more important to the extent that they had more elaboration. Experiment 2 suggested that elaboration increases importance by providing insight into the elaborated component. Too technical information, which was viewed as moderately important, but was too technical to contribute insight to the elaborated information, failed to increase the importance of the elaborated information.

These findings raise a number of questions for future research. Components of stories (van den Broek, 1988) and features of concepts (Sloman, Love, & Ahn; 1998) with causal relationships have been found to be particularly important. What role do causal relationships play in scientific explanations? In other research, we have found that the causal relationships do not predict importance as well as elaboration relationships. Still, the underlying web of causal relationships that constitute phenomena like diabetes and the circadian rhythm likely influence what information people view as mechanistically important. For example, a statement like “there are three types of Diabetes” is not a cause or effect, but it does convey mechanistic information about biological pathways, which likely contributes to its importance.

Additionally, explanations are extremely diverse both in terms of the phenomena they describe and the goals of the explainer and reasoner. For example, someone might desire to know about GPS so that he or she can use a handheld GPS instead of understanding more generally how GPS works. In the real world, people approach explanations from many different perspectives and with different goals. Still, elaboration may play a role. Consider an explanation of why World War I occurred (e.g., mutual alliances, imperialism, and nationalism). This explanation is different from those in the experiments because 1) it deals with historical events which were irrelevant in the current experiments and 2) it focuses on a specific target, why World War I occurred, not just a general understanding of how something works. Still, parts of the explanation with the more elaboration will likely be viewed as more important (e.g., if nationalism was elaborated upon, one might view it as more important). Experiment 2 suggests that in order for elaboration on nationalism to increase the perceived importance of nationalism, the elaboration would actually have to facilitate the reasoner’s understanding. Merely using political jargon about nationalism would not be sufficient. In sum, even though there are many different types of explanations and different goals, these findings may still apply.

In conclusion, the current experiments present novel methods to examine how people determine which components are most important in an explanation. The results demonstrate that people piece together the structure of elaboration relationships between components and use the *structure* and *insight* provided by elaboration to identify important components. These processes may be essential and continuous in everyday cognition and may play a critical role in helping us prune down an overwhelming thicket of information into a more digestible form.

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