Inquiry, Theory-Formation, and the Phenomenology of Explanation

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Abstract

Explanations not only increase understanding; they are often deeply *satisfying*. In the present research, we explore how this phenomenological sense of "explanatory satisfaction" relates to the functional role of explanation within the process of inquiry. In two studies, we address the following questions: 1) Does explanatory satisfaction track the epistemic, learning-directed features of explanation? and 2) How does explanatory satisfaction relate to both antecedent and subsequent curiosity? In answering these questions, we uncover novel determinants of explanatory satisfaction and contribute to the broader literature on explanation and inquiry.

Keywords: explanation; curiosity; theories; inquiry; learning

Humans have an insatiable drive to explain the world around them, and this drive plays an important role in supporting our amazing capacity to learn (Lombrozo, 2012, 2016). In fact, some have suggested that explanation is to theory-building as orgasm is to reproduction (Gopnik, 2000): the phenomenological sense of satisfaction that accompanies an explanation motivates theory-building, just as orgasm motivates reproduction. In the present research, we investigate this hallmark phenomenological component of explanation ("explanatory satisfaction"). What makes an explanation satisfying, and how does this phenomenological sense function to support learning and theory-formation?

Following Gopnik (2000), we assume explanations are comprised of two elements: an epistemic element and a phenomenological element. The epistemic element of an explanation is straightforwardly related to the process of theory-formation and inquiry: broadly, an explanation includes theory-relevant information, which enables learning and facilitates future prediction and intervention. The phenomenological element, on the other hand, is best characterized as an affective response (Gopnik, 2000), and its role in the process of theory-formation and inquiry is less clear. In the present research, we address two questions that situate explanatory satisfaction within this broader process.

First, how does the phenomenological component of explanation relate to the epistemic component of explanation? If explanatory satisfaction plays a functional role in the process of theory-building and inquiry, we might expect explanations to be found more satisfying when they possess features that suggest the epistemic function of explanation has been achieved. We refer to such features as "learning-directed," as they relate to the epistemic role explanation plays in learning. For instance, we might expect explanations to be deemed more satisfying when they identify novel, useful, and generalizable patterns in the environment, or when they possess explanatory virtues (such as simplicity and breadth) that support correspondingly simple and broad theories. Our first research question is whether explanatory satisfaction is indeed influenced by these learning-directed features.

Second, how does explanatory satisfaction relate to *curiosity*, another affective state that often drives explanation-seeking and exploration? Does curiosity about the answer to a given question increase the explanatory satisfaction experienced upon receiving the answer? Do satisfying explanations terminate inquiry by satisfying curiosity, or do they stimulate further inquiry by prompting curiosity about related matters?

In addressing these questions, our studies are among the first to consider explanatory satisfaction within a broader process of inquiry and theory-building, tying the phenomenological component of explanation to its epistemic role ("learning-directed" considerations), and linking it to other affective states that influence learning (namely curiosity). We briefly review prior work on explanatory satisfaction and curiosity before presenting two novel studies.

Prior Work on Explanatory Satisfaction

Research on explanatory preferences and judgments of explanation quality has shown that people prefer explanations that are simple in the sense that they appeal to few unexplained causes (Bonawitz & Lombrozo, 2012; Lombrozo, 2007; Pacer & Lombrozo, 2017; see also Thagard, 1989), and broad in two senses: in that they explain all the relevant features of what's currently being explained (Johnson, Johnston, Toig, & Keil, 2014; Pennington & Hastie, 1992; Thagard, 1989), and in that they explain additional phenomena as well (Preston & Epley, 2005). Other research has found that people prefer explanations with reductive mechanism information (Hopkins, Weisberg, & Taylor, 2016), that appeal to the function of the thing being explained (Kelemen & Rosset, 2009), that have a narrow "latent scope" (Khemlani, Sussman, & Oppenheimer, 2011), and that cite information "inherent" to what is being explained (Cimpian & Salomon, 2014).

There is also evidence that explanations are favored when they are believed to be generalizable and well-suited to future goals. For example, people find functional explanations more acceptable when they appeal to a generalizable causal process (Lombrozo & Carey, 2006). They also judge such explanations better (relative to

category-based or mechanistic explanations) when they anticipate making future inferences on the basis of information about an entity's function as opposed to information about its category membership or the mechanism by which it operates (Vasilyeva, Wilkenfeld, & Lombrozo, 2017). Additionally, it has been proposed that the "explanatory virtues" that have been tied to explanatory satisfaction—simplicity and breadth—are important exactly because they point to the value of an explanation in guiding future inference and action (Lombrozo, 2016; Pacer & Lombrozo, 2017; see also Vasilyeva, Blanchard, & Lombrozo, 2018). Consistent with this idea, research finds that prompts to explain make children and adults more likely to discover simple and broad patterns, improving learning under some conditions (for a review, see Lombrozo, 2016).

Taken together, this work suggests that explanatory satisfaction may be driven in part by features of explanations relevant to learning and theory-formation. Very little work, however, has investigated the relationship between judgments of explanatory satisfaction and learning-directed considerations more directly. In one study, Zemla, Sloman, Bechlivanidis, and Lagnado (2017) presented participants with explanations drawn from an on-line forum, and had them rate the explanations on several dimensions, including what they called novelty ("I learned something new from this explanation"), generality ("This explanation appeals to a general principle [that is, a general rule that applies to many things]"), perceived expertise ("This explanation was written by an expert in this topic"), and quality ("This is a good explanation"). Novelty and generality were moderately correlated with quality, though these correlations were not significant after correcting for multiple comparisons. There was also evidence of a preference for *complexity* over simplicity: participants favored explanations involving multiple causal mechanisms. These findings hint at possible relationships between learning-directed considerations and judgments of explanation quality, but many questions remain open. In particular, which learning-directed features might predict explanatory satisfaction, and when and why is simplicity versus complexity favored? In Studies 1-2, we consider how judgments of learning, utility, simplicity, complexity, expertise, and breadth relate to explanatory satisfaction.

Prior Work on Curiosity and Epistemic Emotions

Recent work on *explanation-seeking curiosity* has investigated what triggers curiosity about why something is the case, motivating a learner to seek an explanation (Liquin & Lombrozo, 2018). In this work, participants received explanation-seeking questions posed in an on-line forum, and rated the questions along a variety of dimensions, including curiosity ("How curious are you about the answer to this question?"). Anticipated learning, generality, and future utility were among the strongest predictors of curiosity. Complexity and expertise were also found to be positive predictors of curiosity. However, it is not known whether curiosity about an explanation affects the perceived quality of or rated satisfaction with that explanation once obtained. In Studies 1-2, we consider whether antecedent curiosity predicts explanatory satisfaction. In Study 2, we additionally consider how explanatory satisfaction affects curiosity for further inquiry.

One reason it is valuable to relate explanation to curiosity is because doing so helps bridge the epistemic role of explanation with the affective and motivational factors that guide (epistemic) behavior. Curiosity is often characterized as an *epistemic feeling* or *emotion* (alternatively referred to as a noetic feeling; Arango-Muñoz, 2014; de Sousa, 2009; Dokic, 2012; Morton, 2010): one of a class of evaluative appraisals of one's own knowledge, which have a distinctive phenomenology and guide epistemic action (de Sousa, 2009). While a full treatment of epistemic emotions is beyond the scope of this paper, linking explanatory satisfaction to curiosity and learning is a step towards a more complete account of how the phenomenological and epistemic roles of explanation function together to support effective learning.

Study 1

In Study 1, we present participants with why-questions and their corresponding answers. In addition to having them indicate the extent to which they find each answer satisfying ("explanatory satisfaction"), we have them rate each answer along a variety of epistemically-relevant dimensions. We also have them rate their curiosity about the answer to each question prior to receiving it. This design allows us to address two related questions.

First, we ask about the role of learning and theory-building considerations in determining explanatory satisfaction. To do so, we have participants indicate the extent to which each explanation teaches them something new, and whether the information it offers is useful and generalizable. We also ask them to evaluate the extent to which each explanation is simple, broad (in the sense of applying beyond what is being explained), and required expertise to produce. We can then evaluate whether and how strongly these factors predict explanatory satisfaction.

Second, we ask how curiosity about an explanation affects explanatory satisfaction. Specifically, are the explanations offered in response to questions that elicit high levels of curiosity judged more satisfying than those offered in response to questions that elicit lower levels of curiosity?

By answering these questions, we shed light on how explanatory satisfaction relates to the epistemic features of explanations and to curiosity, another epistemic emotion that drives inquiry.

Method

Participants Participants in Study 1 were 159 adults (77 male, 78 female, 2 other, and 1 prefer not to specify, ages 19-68) recruited from Amazon Mechanical Turk. Participation was restricted to MTurk workers in the United States, who had completed at least 1000 prior tasks with a

Table 1: Items (each rated on a seven-point scale) for explanatory satisfaction and learning-directed features in Studies 1-2.

Dimension	Full text of item
Satisfaction	How satisfying do you find the answer to this question?
Actual Learning	To what extent has the answer to this question taught you something new?
Learning Potential	Do you think there is something to be learned from the answer to this question (even if you yourself already knew the answer)?
Expertise	Do you think that answering this question required special expertise in some domain?
Simplicity	Do you think the answer to this question is simple or complex?
Breadth	Do you think the answer to this question is narrow (only applies to what is being explained) or broad (also applies to other similar cases)?
Future Utility	To what extent will the answer to this question be useful to you in the future?
Regularity	Do you think the answer to this question helps reveal a genuine pattern, structure, or regularity?

minimum approval rating of 99%. Forty additional participants completed the study but were not included in analyses because they did not pass two attention checks.

Materials Fifty-six questions and answers were selected from the book *1000 Questions & Answers Factfile* (Kerrod, Madgwick, Reed, Collins, & Brooks, 2006). For example, the question "Why do some stars explode?" was answered with the following explanation: "Massive stars explode when they come to the end of their lives. They swell up into huge supergiants. Supergiants are unstable, so they collapse and blast into pieces in an explosion called a supernova. Supernovae are the most intense explosions in the universe, as bright as billions of suns put together."

Procedure Each participant saw four questions randomly selected from the 56 questions described above. Participants first rated their curiosity about each question ("Consider the following: *[question premise]*. How curious are you about why this is the case?"). Participants also rated seven items that are not relevant to the present research and are not reported here. Next, participants completed seven arithmetic problems; those who did not correctly respond to at least five items were excluded.[1] After this task, participants read the answer to each of the four questions, and rated each answer on explanatory satisfaction and several learning-directed features (see Table 1). Finally, participants completed a memory check, which required selecting four of the questions presented during the rating tasks from a list with four distractor questions. Participants were given one point for each correct response (hit or correct rejection), and those who scored fewer than six points were excluded.

Results

Due to the nested structure of the data, all analyses used a mixed-models approach, with random intercepts for participant and item in all models. Standardized regression coefficients are reported; all reported coefficients reached significance at the $p < .05$ level using likelihood ratio tests. In addition to the results reported here, all regression analyses were repeated controlling for the length of the explanation in number of words, as prior work has shown that longer explanations tend to be more satisfying (Weisberg, Taylor, & Hopkins, 2015). Controlling for explanation length had no effect on our results.

Learning-Directed Features First, we tested the role of learning-directed considerations in predicting explanatory satisfaction. To do so we fit a regression model predicting satisfaction with all learning-directed considerations entered simultaneously as fixed effects. Only actual learning, β = 0.26, 95% CI [0.17, 0.34], learning potential, β = 0.18, 95% CI [0.10, 0.26], and future utility, β = 0.12, 95% CI [0.04, 0.21], explained unique variance in satisfaction holding all other measures fixed (see Figure 1). However, as many of the measures were modestly correlated with each other (see Figure 2), potentially affecting the robustness of the coefficient estimates reported above, we also fit a separate regression model for each measure. Actual learning, β = 0.39, 95% CI [0.32, 0.47], learning potential, β = 0.39, 95% CI [0.31, 0.46], expertise, β = 0.31, 95% CI [0.24, 0.39], simplicity, β = -0.23, 95% CI [-0.30, -0.15], breadth, β = 0.13, 95% CI [0.05, 0.20], future utility, β = 0.25, 95% CI [0.17, 0.33], and regularity, β = 0.17, 95% CI [0.10, 0.25], were all significant predictors of explanatory satisfaction (see Figure 1).

Antecedent Curiosity Next, we tested whether curiosity about the anticipated answer to a question predicted explanatory satisfaction. We found that curiosity was a significant (though modest) predictor, β = 0.19, 95% CI [0.11, 0.26], and that the model including curiosity as a fixed effect was a significant improvement upon the null model, $\chi^2(1) = 23.12$, $p < .001$.

[1] This attention check may assess numeracy, which could lead to unnecessary exclusions that are irrelevant to successful completion of our task. However, when the participants who failed this task are included in all analyses (for Studies 1 and 2), all results remain unchanged.

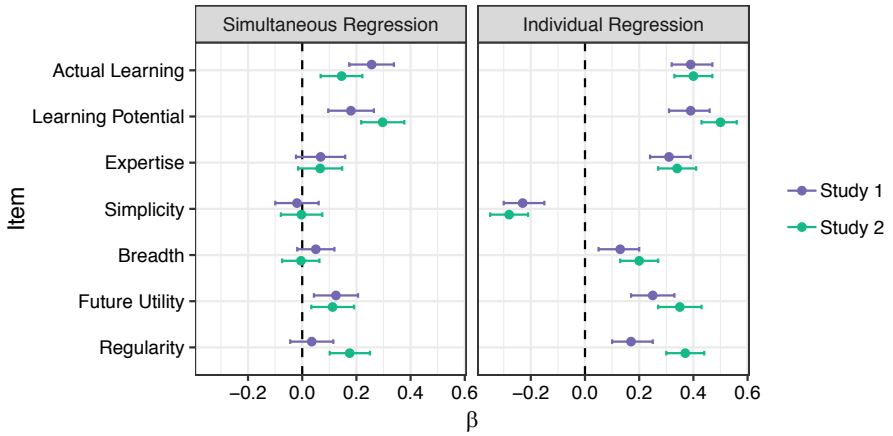

Figure 1: Study 1 and Study 2 standardized regression coefficients for each measure predicting explanatory satisfaction, in a simultaneous regression model (left panel) and in individual regression models (right panel). Study 2 regression coefficients control for interest and knowledge. Error bars = 95% CI.

Discussion

The findings from Study 1 are largely consistent with previous research on the role of breadth (Johnson et al., 2014; Preston & Epley, 2005), future utility (Vasilyeva et al., 2017), and generalizability (Lombrozo & Carey, 2006) in driving explanatory satisfaction. However, one important qualification is that *complexity*, rather than *simplicity*, led to higher ratings of explanatory satisfaction. This is surprising in light of prior work documenting a preference for simpler explanations when using well-controlled stimuli (where, for example, probability is matched; Lombrozo, 2007, Pacer & Lombrozo, 2017), but is consistent with prior work using more naturalistic stimuli, such as those employed here (e.g., Zemla et al., 2017).

Our findings go beyond prior work in identifying an important role for our new learning-directed measures of actual learning, learning potential, and expertise. In fact, these were among the strongest predictors of explanatory satisfaction. We also found a modest role for antecedent curiosity, in that greater curiosity about the answer to a question predicted greater satisfaction with the answer. While this has not (to our knowledge) been tested in prior research, there is evidence that the gap between curiosity about the answer to a trivia question and the satisfaction upon receiving the answer predicts later memory for the answer (Marvin & Shohamy, 2016). This suggests that how much is learned from an explanation could be a function of *both* antecedent curiosity and the explanatory satisfaction experienced from the explanation itself.

These findings highlight the value of approaching the study of explanatory satisfaction through the lens of theory-formation and inquiry. In particular, if achieving explanatory satisfaction effectively motivates learning and theory-formation, then we should expect a close correspondence between explanatory phenomenology and the epistemic functions of explanation. Our findings provide initial support for this correspondence.

Study 2

In Study 2, we replicate the key findings from Study 1, while controlling for two potentially relevant factors: participants' a priori interest in and knowledge about the topics the explanations address. We also investigate how explanatory satisfaction relates to the ongoing process of inquiry (for a discussion, see Danovitch & Mills, 2018) by considering how explanatory satisfaction affects subsequent curiosity. We propose two competing hypotheses: First, it is possible that the receipt of a satisfying explanation will halt further inquiry. Supporting this hypothesis, Frazier, Wellman, and Gelman (2009) found that preschoolers in both naturalistic and experimental settings were less likely to re-ask a question following an explanation (vs. a non-explanation) from an adult, suggesting that the receipt of an explanation stopped further inquiry, at least concerning the topic in question. Relatedly, Mills, Sands, Rowles, and Campbell (2019) found that children were more likely to request additional information in response to explanations that they rated as less-complete answers to the relevant question, relative to more-complete explanations.

However, it is also possible that receiving a satisfying explanation could *promote* further inquiry. Even a satisfying explanation will often highlight new things the learner does not yet know, promoting further exploration and information search. For example, Liquin and Lombrozo (2017) found that generating explanations during learning increased information search in the face of surprising evidence (see also Legare, 2012). Moreover, some theories of curiosity posit that curiosity peaks when there is a modest "gap" between a learner's current and desired knowledge state, resulting in an inverted-U-shaped relationship between prior knowledge and curiosity (Loewenstein, 1994). For learners on the ascending side of the "U," a satisfying explanation could result in *greater* curiosity.

To distinguish between these hypotheses, we ask participants to rate their curiosity about several follow-up questions in response to an explanation, after completing the

same ratings as in Study 1. If explanatory satisfaction halts inquiry, we would expect greater satisfaction to predict lower curiosity about follow-up questions. By contrast, if explanatory satisfaction promotes inquiry, we would expect greater satisfaction to predict greater curiosity about follow-up questions.

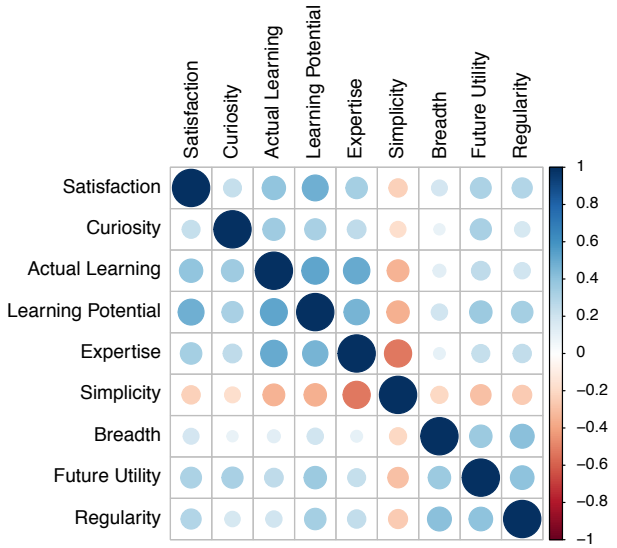

Figure 2: Matrix of pairwise correlation magnitudes for all measures of interest (collapsed across Study 1 and Study 2 data).

Method

Participants One hundred seventy-one adults (96 male and 75 female, ages 21-69) from Amazon Mechanical Turk participated in Study 2. Participation was restricted to MTurk workers in the United States who had completed at least 1000 HITs with a minimum approval rating of 99%. Twenty-nine additional participants completed the study but were excluded from analysis because they did not pass the same attention checks used in Study 1.

Materials Of the 56 questions and answers used in Study 1, twenty were randomly selected for use in this study. An initial sample of 48 MTurk participants read random samples of five question-answer pairs and wrote between 3 and 10 follow-up questions in response to each answer. From this set of follow-up questions, we randomly selected 10 for each question-answer pair. Thus, the materials used in this study were 20 question-answer pairs from *1000 Questions & Answers Factfile* (Kerrod et al., 2006), with 10 follow-up questions in response to each. Additionally, each question was classified into a "topic area," based loosely on the chapter and page topics in the *1000 Questions & Answers Factfile* book. The 20 questions fell into 14 distinct topic areas (e.g., "dinosaurs," "stars," "Ancient Egypt").

Procedure First, each participant rated their interest in and knowledge about each of the 14 topic areas described above. Then, each participant saw four questions randomly selected from the 20 questions. For each question, they completed the initial curiosity rating, followed by the arithmetic distractor/attention task, as in Study 1. Then, two tasks were presented in a randomized order: the answer ratings, as described in Study 1, and the follow-up question task. For the latter task, participants saw a random sample of five of the ten follow-up questions for each of the four questions (presented with answers) that they had seen previously. For each follow-up question, participants rated how curious they were about the answer to that question on a seven-point scale. These five ratings were averaged within each of the four questions, creating a "follow-up curiosity" scale for each question rated by each participant (Cronbach's α = 0.85).

Results

Results were analyzed as in Study 1, using a mixed-models approach. Again, all results remained unchanged when controlling for explanation length.

Replications of Study 1 First, we repeated all analyses from the previous study, but controlling for interest in and knowledge of the topics corresponding to the question-answer pairs. In a simultaneous regression model, actual learning, β = 0.14, 95% CI [0.07, 0.22], learning potential, β = 0.30, 95% CI [0.22, 0.38], future utility, β = 0.12, 95% CI [0.04, 0.20], and regularity, β = 0.18, 95% CI [0.10, 0.25], explained unique variance in satisfaction holding all other measures fixed (see Figure 1). In separate regression models, actual learning, β = 0.40, 95% CI [0.33, 0.47], learning potential, β = 0.50, 95% CI [0.43, 0.56], expertise, β = 0.34, 95% CI [0.27, 0.41], simplicity, β = -0.28, 95% CI [-0.35, -0.21], breadth, β = 0.20, 95% CI [0.13, 0.27], future utility, β = 0.35, 95% CI [0.27, 0.43], and regularity, β = 0.37, 95% CI [0.30, 0.44], were all significant predictors of explanatory satisfaction (see Figure 1). Curiosity was also a significant predictor of explanatory satisfaction, controlling for interest and knowledge, β = 0.19, 95% CI [0.11, 0.26].

Satisfaction and Inquiry Next, we tested the relationship between explanatory satisfaction and subsequent curiosity. To do so, we compared a model predicting average follow-up curiosity with satisfaction as a fixed effect to a null model with no fixed effects. Satisfaction was a significant predictor of follow-up curiosity, $\chi^2(1) = 45.20$, $p < .001$. Critically, the relationship between satisfaction and follow-up curiosity was positive, β = 0.22, 95% CI [0.16, 0.29], indicating that explanatory satisfaction, at least in this context, *encourages* rather than halts ongoing inquiry.

Finally, we repeated this analysis, but controlling for interest in and knowledge of the topics corresponding to the question-answer pairs. Satisfaction remained a significant predictor of follow-up curiosity, β = 0.21, 95% CI [0.14, 0.27], $\chi^2(1) = 40.45$, $p < .001$.

Discussion

In Study 2, we replicated the results of Study 1 while

controlling for topic knowledge and interest, again demonstrating that learning-directed features predict explanatory satisfaction, and that curiosity about an explanation-seeking question predicts satisfaction with the answer.

Study 2 also investigated how explanatory satisfaction relates to subsequent curiosity. We found support for the hypothesis that explanatory satisfaction encourages rather than halts inquiry—that is, the more satisfied a participant was with a given explanation, the more curious they were about several follow-up questions. This is in contrast to past work demonstrating a negative relationship between explanation *completeness* and subsequent information search (Frazier et al., 2009; Mills et al., 2019). This could reflect methodological differences in what was evaluated (explanatory completeness versus satisfaction), or in the opportunities for further inquiry that were offered. For instance, we might expect inquiry concerning the original explanandum to cease after obtaining a satisfying explanation, but for inquiry concerning related matters to be piqued. These questions merit further research.

General Discussion

Explanations play an important role in the process of inquiry: they contribute to learning and theory-building, which in turn support predictions, interventions, and understanding. Explanations also have a unique phenomenology that may motivate this theory-building behavior. However, most research on explanation has not directly addressed how this phenomenology relates to the functional role of explanation within the process of theory-formation and inquiry. In the present research, we addressed two questions: 1) To what extent is explanatory satisfaction driven by features of an explanation that support learning and theory-formation? and 2) How does explanatory satisfaction relate to *curiosity*, another epistemic emotion that motivates inquiry?

In response to the first question, we find that several learning-directed features (such as actual learning, learning potential, future utility, and regularity) are related to explanatory satisfaction, even when controlling for interest in and knowledge of the topics addressed by the explanation. Answering the second question, we find that antecedent curiosity predicts satisfaction with a subsequent explanation to a modest degree, and that explanatory satisfaction in turn predicts curiosity about follow-up questions in response to an explanation, thus encouraging further inquiry.

These studies build upon previous research on explanatory satisfaction and explanation-seeking behavior. In particular, we replicate previous research on the role of breadth, generalizability, and future utility in explanatory satisfaction, and we find several additional predictors of explanatory satisfaction that have not previously been explored—or for the case of learning, that have not previously found strong support (Zemla et al., 2017). Additionally, we add to recent research on curiosity (Liquin & Lombrozo, 2018; Marvin & Shohamy, 2016), demonstrating a systematic relationship to explanatory satisfaction throughout the process of inquiry.

Several limitations of these studies must be noted. First, future work should explore a broader range of materials, including "everyday" questions and explanations from more ecologically-valid settings. Second, the findings we report are all correlational, so it remains to be seen whether (for example) curiosity about an explanation *causes* satisfaction with the later-received explanation. More critically, these studies do not cleanly disentangle the phenomenological component of explanation from the epistemic component. That is, participants' ratings of explanatory satisfaction likely reflected affective responses (perhaps in contrast to ratings of goodness, quality, or completeness, which have often been used in past research; e.g., Mills et al., 2019; Vasilyeva et al., 2018; Zemla et al., 2017), but also evaluation of (epistemic) quality, which may not have been accompanied by any particular phenomenology. For our purposes, the key question is whether and how explanatory satisfaction motivates inquiry, so it is notable that in Study 2, there was a positive relationship between explanatory satisfaction and ongoing curiosity. Future work should explore the relationship between explanatory satisfaction and subsequent epistemic *behaviors*, such as information search, as well as epistemic *consequences*, such as learning.

Another possible limitation of this work is that participants only read a single explanation in response to each question, while previous work on explanatory preferences (e.g., Lombrozo, 2007; Pacer & Lombrozo, 2017) has typically used *comparative* judgments of explanation quality between two competing explanations. As a result, satisfaction judgments in the present research may reflect satisfaction that an explanation *exists*, rather than satisfaction that this explanation fulfills certain explanatory desiderata relative to other possible explanations. Future work should explore whether different criteria are used to evaluate explanations presented simultaneously versus in isolation.

Despite these limitations, these studies are among the first to approach explanatory satisfaction in terms of its functional role within a broader process of inquiry, providing new insights into the determinants of explanatory satisfaction and the importance of this phenomenology in driving ongoing inquiry and theory-building.

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