emotion review

Emotion Review
Vol. 9, No. 3 (July 2017) 1–7

ISSN 1754-0739
DOI: 10.1177/1754073916673212
journals.sagepub.com/home/er

Science Is Awe-Some: The Emotional Antecedents of Science Learning

Piercarlo Valdesolo
Department of Psychology, Claremont McKenna College, USA

Andrew Shtulman
Department of Cognitive Science, Occidental College, USA

Andrew S. Baron
Department of Psychology, University of British Columbia, USA

Abstract

Scientists from Einstein to Sagan have linked emotions like awe with the motivation for scientific inquiry, but no research has tested this possibility. Theoretical and empirical work from affective science, however, suggests that awe might be unique in motivating explanation and exploration of the physical world. We synthesize theories of awe with theories of the cognitive mechanisms related to learning, and offer a generative theoretical framework that can be used to test the effect of this emotion on early science learning.

Keywords
awe, learning

Scientists from Einstein to Sagan have written at length about the capacity of emotional states like awe to deeply engage scientific inquiry (Sagan & Druyan, 2006), yet no psychological theory has linked these phenomena conceptually. Research on the emotional antecedents of learning has been growing, but most of this initial work has focused on the effects of valence (positivity/negativity) on learning outcomes. For example, a large body of literature exists looking at how achievement and mastery goals are hindered by test anxiety (Goetz, Frenzel, Hall, & Pekrun, 2008; Linnenbrink, 2006; Pekrun, Goetz, Titz, & Perry, 2002) or facilitated by positive affect (Kaplan & Maehr, 1999; Linnenbrink, 2005; Meece, Blumenfeld, & Hoyle, 1988; Nicholls, Patashnick, & Nolen, 1985; Nolen & Haladyna, 1990; Pintrich, 2000; Roeser, Midgley, & Urdan, 1996; Seifert, 1995). Recent research on science learning has begun to acknowledge the importance of examining distinctions amongst discrete emotional states (Pekrun, Elliot, & Maier, 2009; Pekrun et al., 2002; Sinatra, Broughton, & Lombardi, 2014), but it has not yet considered emotions like awe.

We propose a theory that seeks to fill this significant gap in the literature in the context of early science education. We hypothesize that awe is the emotional state most likely to impact outcomes in science learning, from investigating scientific problems to retaining scientific information. We ground this proposal in theories of the emotion's antecedents, its conceptual distinction from similar emotional states (e.g., surprise, curiosity, and wonder), and empirical demonstrations of its effect on processes related to cognitive accommodation, a crucial determinant of science learning. We highlight how readily the existing conceptual and empirical work on the antecedents and consequences of awe can be integrated with theory and research on learning. In short, processes that have separately been found by cognitive developmentalists to underlie science learning (i.e., violations of learners' expectations, uncertainty-driven exploration and explanation of the physical world, cognitive accommodation and conceptual change) have been both theoretically and empirically linked to the experience of awe by affective scientists. Our theory unites two previously disparate areas of research, and highlights the importance of research on the relation between discrete emotional states and learning moving forward. It not only adds to existing theories of learning

Corresponding author: Piercarlo Valdesolo, Department of Psychology, Claremont McKenna College, Claremont, CA 91711, USA. *Email*: pvaldesolo@cmc.edu

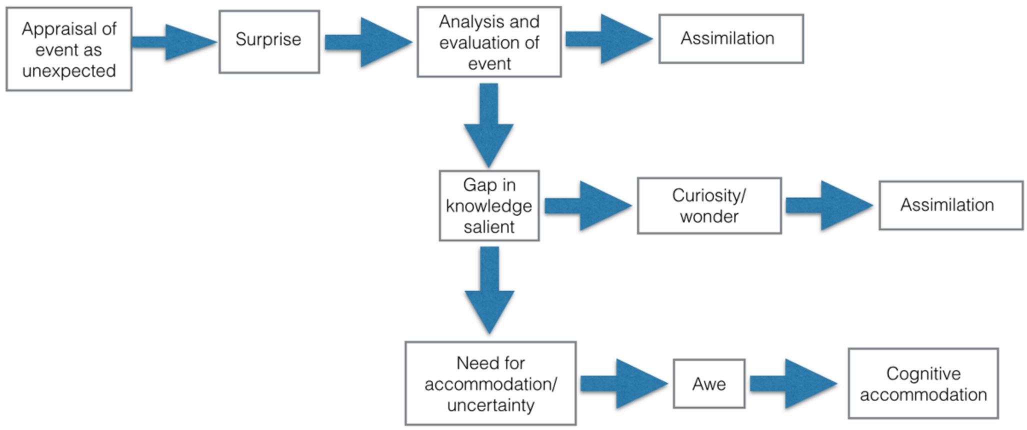

Figure 1. Model of the conceptual distinctions between related epistemic emotions.

and emotion, but could also provide a roadmap for future research on how to develop pedagogical techniques for more effectively triggering this emotion in the service of science education.

Epistemic Emotions

Awe belongs to a family of emotions that can be labeled "epistemic." These affective states are defined by their relation to knowledge and understanding, and have been studied in a variety of ways with respect to processes associated with learning outcomes (e.g., attention, exploration, and explanation-seeking). But the relationship between these states has thus far been ambiguous, with researchers either using the terms interchangeably or defining certain states as blends or variants of others. For example, awe has been defined as a *kind* of interest (Izard, 1977), possibly leading to curiosity, as well as related to feelings of surprise (Frijda, 1986). The terms awe and wonder have not been distinguished empirically, with wonder often being included in composite measures of awe (e.g., Shiota, Keltner, & Mossman, 2007).

Though researchers seem to agree that all these emotions are triggered when gaps in our existing knowledge are made salient (Kashdan, Sherman, Yarbro, & Funder, 2013; Loewenstein, 1994; Silvia & Kashdan, 2009), and are thought to influence processes related to acquiring or revising that knowledge, there are important distinctions between them. In what follows we flesh out these distinctions and why their unique properties matter for our proposal that the experience of awe in particular would be particularly conducive to early science learning. We summarize our analysis in Figure 1.[1]

Surprise

Surprise has attracted the most empirical attention and is thought to be elicited any time there is a discrepancy between an existing schema and a current input (Reisenzein, Meyer, & Niepel, 2012; Schützwohl, 1998). Intensity of surprise maps onto the degree of unexpectedness of the surprising event (Stiensmeier-Pelster, Martini, & Reisenzein, 1995). But importantly, an unexpected event can be surprising even if it can be explained easily. For example, one might be surprised by family members jumping out from behind a couch at a birthday party. Experimental manipulations of surprise are consistent with this conceptualization, using simple techniques such as unannounced changes of computer stimuli to evoke the emotion (Reisenzein & Studtmann, 2007). These kinds of events do not require effortful assimilation or explanation to understand, and it is this feature that we believe distinguishes surprise from other states like curiosity, wonder, and awe. Though some research has linked complexity of explanation for an event with intensity of surprise (Foster & Keane, 2015), this research did not measure other similar states, and work that has done so has found important distinctions in the kinds of events that elicit surprise and other epistemic emotions (e.g., Shiota et al., 2007).

Curiosity and Wonder

If an explanation for an unexpected event is not obvious, and an effortful causal search is required in order to assimilate information, then we propose the emotional state generated by the event is best described as curiosity or wonder. We refer to curiosity and wonder as conceptually similar emotional states characterized not only by the presence of an unexpected event but the salience of a gap in current knowledge and a desire and need to acquire more information in order to explain that event. Experimental inductions of curiosity map onto this definition, the most common of which is presenting trivia questions that participants cannot answer but may desire to know the answer (Gruber, Gelman, & Ranganath, 2014; Kang et al., 2009). No empirical work to our knowledge has studied wonder per se. Though the term has been used in composite scales of awe (Saroglou, Buxant, & Tilquin, 2008) it is often used interchangeably with curiosity in language to refer to a positively valenced approach state geared towards acquiring knowledge (e.g., "I am curious about," "I wonder about"). We adopt this latter definition. Curiosity and wonder do not require the accommodation (or restructuring) of existing mental structures in order to make sense of an event. They are thought to be evoked only by relatively minor violations of expectations, while violations that represent major threats to understanding either evoke fear-like aversive reactions (Hebb, 1949; Loewenstein, 1994) or are simply ignored because of an inability to assimilate the new information into existing mental structures (Chinn & Brewer, 2001).

Awe

Awe is triggered by an unexpected event, like surprise, and involves the salience of a gap in knowledge and a desire to acquire more information, like curiosity and wonder, but it also entails an inability to assimilate information into existing mental structures and a resulting need for accommodation. Distinct from curiosity and wonder, awe seems to be evoked by major violations of expectations that, while they can evoke feelings of uncertainty and confusion, also motivate explanation-seeking via a need for cognitive accommodation. Consistent with this conceptualization, awe can be both positively or negatively valenced and can be characterized by either approach or avoidance motivations (Keltner & Haidt, 2003), likely depending on individual differences in constructs such as the need for cognitive closure and openness to experience (Shiota et al., 2007) or perceptions of threat or great power in the awe-evoking stimulus. A growing body of empirical literature supports this conceptual definition of awe, and it is the accommodative component of the awe experience that distinguishes it from other epistemic emotions.

Awe has been defined in a variety of ways. For example, Ekman (1992) speculated that awe would likely be found to satisfy all commonly accepted criteria for inclusion as a basic emotion, but he offered no framework for understanding its causes or consequences.

Taking up this challenge, Keltner and Haidt (2003) developed a full conceptual framework of awe that has shaped contemporary research into this emotion. Their theory identifies two core components of this affective experience: a *perception of vastness* and a *need for accommodation*. On this view, awe is triggered when in the presence of something that cannot be understood in terms of one's current theories of the world (i.e., it is perceptually vast) and that involves a strong motivation to adjust those theories in order to make sense of the novel stimulus (i.e., a need for accommodation). This conceptualization is grounded directly in Piagetian theories of cognition (Piaget, 1971), on which we process new information either by assimilating that information into preexisting schemas or by changing our preexisting schemas to accommodate the new information. Awe is thought to be evoked when we confront information that cannot be assimilated into preexisting schemas and, consequently, triggers accommodation instead. While developmental psychologists have moved away from the terms "assimilation" and "accommodation" in the decades since Piaget, the processes themselves continue to play a valuable role in research on conceptual development, differentiating easy, run-of-the-mill learning ("knowledge enrichment") from learning that is more effortful and more protracted ("knowledge restructuring" or "conceptual change"). The former is synonymous with assimilation, whereas the latter is synonymous with accommodation (Carey, 2009).

Keltner and Haidt's framework has inspired several lines of research into the cognitive and behavioral consequences of awe, and while much of it remains in the early stages, one empirical result has reliably emerged: awe involves feelings of uncertainty. Uncertainty, which is generally a negative psychological state, results from failures of assimilation (Keltner & Haidt, 2003), and research suggests that the desire to reduce this uncertainty constitutes the main motivation behind cognitive accommodation. For instance, Shiota et al. (2007) found a correlation between dispositional awe-proneness (example item: "I often feel awe") and the need for cognitive closure (an index of an individual's discomfort with uncertainty and desire for consistency; Webster & Kruglanski, 1994). Specifically, awe-prone individuals were less likely to demonstrate such a need, suggesting that individuals who chronically experience awe are more comfortable with uncertainty. Griskevicius, Shiota, and Neufeld (2010) found a complementary effect showing that experimentally manipulated awe leads to increased feelings of uncertainty. These studies also showed that awe leads to more systematic cognitive processing and that this relationship is mediated by feelings of uncertainty—a result interpreted as demonstrating that feelings of uncertainty motivate a drive for increased understanding. Indeed, while other positive emotions tend to increase reliance on heuristics and stereotypes when processing novel information (Griskevicius et al., 2010), awe is unique in that it does the opposite: it motivates systematic processing of information geared towards understanding and explaining the awe-inducing event. In short, feelings of uncertainty motivate a drive for increased understanding as a means of accommodating novel information.

Building off this work, Valdesolo and Graham (2014) and Valdesolo, Park, and Gottlieb (2016) directly tested whether awe would increase explanation-seeking and whether feelings of uncertainty might represent the motivational force behind this effect. They did so in the distinct domains of scientific and supernatural thought. On their surface, scientific and supernatural thought offer competing explanations for natural events (Preston & Epley, 2009), but research in anthropology (Frazer, 1922/1998) and psychology (Rutjens, van der Pligt, & van Harreveld, 2010) suggests that they stem from the same underlying motivation: the need to explain, predict, and control the natural world (Preston, 2011; Shtulman & Lombrozo, 2016). A large body of literature has shown that explaining events via either religious frameworks (Kay, Whitson, Gaucher, & Galinsky, 2009) or scientific frameworks (Rutjens, van Harreveld, van der Pligt, Kreemers, & Noordewier, 2013) can buffer against the aversive state of uncertainty, and, consistent with that literature, Valdesolo and Graham (2014) found that awe increased affinity for supernatural explanations as a function of how strongly it raised feelings of uncertainty. Similarly, Valdesolo et al. (2016) found that the effect of awe on attraction to either religious explanations or scientific explanations depends on preexisting explanatory commitments. Individual differences in theism moderated the effect of awe on the kind of explanations to which participants were attracted. Taken together, this work shows how awe motivates explanation-seeking as a function of its relation to uncertainty, and points to the possibility that the need for accommodation that accompanies awe experiences may influence explanation-seeking in ways that are unique from other epistemic emotions (i.e., in domains relevant to science learning).

Despite the conceptual ambiguity amongst epistemic emotions, a common component across the theoretical and empirical research on these states has been the proposal that they are elicited by violations of expectation. For example, Griskevicius et al. (2010) write that awe "serves to facilitate new schema formation in unexpected, information-rich environments" (p. 193), Frijda (1986) writes that curiosity and wonder result from the "occurrence of mismatch between stimulus input and preexisting cognitive dispositions (knowledge, expectations)" (p. 346), and surprise has been linked directly to the unexpectedness of an event (Stiensmeier-Pelster et al., 1995).

Currently we know very little about the conditions under which violations of expectation lead to one kind of epistemic emotion versus another. We do know, however, that violating an expectation can lead to outcomes that facilitate learning. We summarize this research in the following lines before turning to why we believe that violations of expectation in the domain of science are particularly likely to elicit awe compared with other epistemic emotions.

Violations of Expectation and Learning

One learning outcome that has been linked to violations of expectation is enhanced memory for the expectation-violating information. In studies where adults were asked to predict the answers to numeric trivia questions, adults were more likely to recall those answers 12 weeks after learning them if the answers fell outside a range of expected values (Munnich, Ranney, & Song, 2007). Violations of expectation lead to enhanced memory in infants as well. Infants who observe physically impossible events, like one object seemingly passing through another, remember the attributes of the objects involved in those events better than infants who observe perceptually similar, yet physically ordinary, events (Stahl & Feigenson, 2015). Increased memory for expectation-violating events appears to be mediated by areas of the brain involved in seeking and monitoring external rewards (the midbrain and the nucleus accumbens), insofar that expectation-violating events arouse curiosity and curiosity-mediated learning is associated with activity in these brain regions (Gruber et al., 2014).

Violations of expectation also lead to increased causal-explanatory reasoning, particularly in children. When preschool-aged children are shown events that violate a preexisting expectation, such as the expectation that a particular kind of object activates a particular kind of machine, they generate more explanations for those events (e.g., "the box is broken," "it ran out of batteries," "you put the toy on the wrong box") than when shown events that conform to that expectation (Legare, Gelman, & Wellman, 2010). Preschoolers will even posit the existence of unobserved causal variables (e.g., a hidden block) to resolve the discrepancy between what they observed and what they expected to have observed (Schulz, Goodman, Tenenbaum, & Jenkins, 2008). In these studies, children's emotional responses to expectation-violating events were not examined, but the motivation behind their explanation-seeking behavior may well be the desire to reduce the uncertainty associated with having their expectations violated.

As children age, the kinds of explanations they posit for expectation-violating events become more sophisticated. Eight-year-olds, for instance, are more likely to cite causal factors like magnetism, buoyancy, or heat transfer as explanations for expectation-defying events than 6-year-olds, and 6-year-olds are more likely to do so than 4-year-olds (Phelps & Woolley, 1994). The ability to provide causal explanations for expectation-violating events develops in tandem with the ability to identify the particular causal principles violated by such events. By age 6, children have begun to differentiate events that violate statistical regularities from those that violate physical laws (Shtulman, 2009; Shtulman & Carey, 2007), and this distinction facilitates their ability to scrutinize expectation-violating events in terms of their underlying causal structure (Shtulman & Yoo, 2015). Children's increased focus on identifying the causes of an anomalous event likely stems from a desire to reduce uncertainty, as causal explanations have been shown to be more satisfying than other kinds of explanations (Keil, 2006; Lombrozo, 2006).

Children who have had their expectations violated are not only motivated to explain the violation but are also motivated to explore the situation that gave rise to the violation. For instance, children whose expectations about shadows are violated in the context of a shadow-projection task spend more time exploring expectation-relevant permutations of the shadow-projection device than children whose expectations are not violated (van Schijndel, Visser, van Bers, & Raijmakers, 2015). Likewise, children whose expectations about physical support are violated in the context of a balance-scale task spend more time exploring expectation-relevant permutations of the balance scale than children whose expectations are not violated (Bonawitz, van Schijndel, Friel, & Schulz, 2012). Critically, the nature of children's exploration accords with the nature of the causal factors they identify as explanations for the violation at hand. For example, when children observe a violation of the expectation that a particular kind of object (a "blicket") activates a particular kind of machine (a "blicket detector"), they will selectively explore either the object or the machine depending on which they have identified as the most plausible source of the violation (Legare, 2012). Thus, children resolve the uncertainty surrounding expectation-violating events not only by positing explanations for those events but also by seeking confirmation that their explanations are correct.

Awe and Violations of Expectations in Science Learning

In sum, there is strong empirical support for the effect of violations of expectation on learning (i.e., exploratory and explanatory behaviors), and strong support for the role of violations of expectations in triggering different epistemic emotions. The empirical work on these topics in combination with our conceptual proposal distinguishing awe from other epistemic emotions suggests that awe might play a unique role in early science learning. The effect of emotional states on learning depends on the content of what is being learned (Broughton, Sinatra, & Nussbaum, 2013), with particular emotional states experienced in some content domains more than others. We believe that science is the domain in which awe plays the greatest role in early learning.

Awe is elicited in the presence of an event that is perceived as a major violation of one's current theories about the world and cannot be assimilated into existing mental structures. The feeling of uncertainty created by this gap between knowledge and experience triggers a need for accommodation (or knowledge restructuring) that promotes explanation and exploration, two crucial antecedents of learning. From an early age, children's expectations relevant to the domain of science are widespread, deeply held, and rooted in intuitive theories of the physical world (Carey, 2000; Wellman & Gelman, 1992). We propose that violations of these expectations would not only make gaps in knowledge salient but would also motivate a need for accommodation that distinguishes the awe experience from other related epistemic emotions. Violations of the physical world related to such phenomena as atoms, genes, planetary motion, inertia, electricity, evolution, or tectonic plates cannot be easily assimilated as they challenge deeply held naïve theories. Seeing, for example, a feather and an anvil drop at the same rate in a vacuum represents a strong violation of intuitive theories of gravity, on which heavy objects fall faster than light ones. Knowing that the objects fell in a vacuum is not sufficient for assimilating that event into one's understanding of physical motion; what one needs to know is how weight differs from gravity and how gravity affects motion.

We predict that these kinds of events will elicit awe above and beyond other epistemic emotions, and that the degree of cognitive accommodation that follows such events, and therefore the degree of success in making sense of this information, will be predicted by experienced awe. In short, awe will drive conceptual change in the domain of science, defined by dissatisfaction with existing theories and motivating the replacement of those theories with new, more accurate ones. The ways in which children accommodate expectation-violating information so as to acquire new scientific theories is one of the most important areas of research in early science education (Bonawitz et al., 2012; van Schijndel et al., 2015), and awe may be particularly influential amongst epistemic emotions in its ability to promote such cognitive activities.

Our theoretical framework paves the way for future research testing the relation between violations of science-relevant expectations, awe, and early science learning outcomes. Specific questions in need of investigation are (a) whether violating children's expectations in a variety of scientific domains does, in fact, increase experiences of awe, (b) whether experiences of awe do, in fact, mediate explanatory and exploratory behavior in scientific domains, and (c) whether instructional techniques can be used to violate children's expectations more effectively and, hence, to elicit awe more effectively prior to and during formal instruction. The answers to these questions will shed light not only on the emotional antecedents of science learning but also on the goal of improving science learning in early childhood. We are optimistic about the feasibility of this empirical project given that expectations in the domain of science have been well studied and well described, and that these expectations are relatively easy to violate in the context of a brief observation or demonstration. Indeed, science content is inherently expectation-violating (Chi, 2005; Nersessian, 1989; Shtulman, 2015; Vosniadou, 1994).

When Socrates said "wisdom begins in wonder," he suggested an important causal relationship between epistemic emotional states and the ultimate production of knowledge and learning. And when the National Research Council adopted the Next Generation Science Standards identifying "wondering, investigating, and questioning" as the basis for K-12 science education, they suggested that the effects of these kinds of emotions may be particularly important to the development of *scientific* wisdom. Though we agree with the implied emphasis on the importance of epistemic emotions in learning in general and science education in particular, we offer a friendly amendment: science is not simply wonderful, it's *awesome*. We urge other researchers concerned with promoting early interest and engagement in science, technology, engineering, and math (STEM) to help us empirically test our theory.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Note

1 *Interest* is a related epistemic emotion but is not discussed here given that it does not necessarily result from violations of expectations (a crucial feature of our conceptual model; cf. Campos, Shiota, Keltner, Gonzaga, & Goetz, 2013 and Sauter, XXXX, for further discussion of interest).

References

Bonawitz, E. B., van Schijndel, T. J., Friel, D., & Schulz, L. (2012). Children balance theories and evidence in exploration, explanation, and learning. *Cognitive Psychology*, *64*, 215–234.

Broughton, S. H., Sinatra, G. M., & Nussbaum, E. M. (2013). "Pluto has been a planet my whole life!" Emotions, attitudes, and conceptual change in elementary students' learning about Pluto's reclassification. *Research in Science Education*, *43*, 529–550.

Campos, B., Shiota, M. N., Keltner, D., Gonzaga, G. C., & Goetz, J. L. (2013). What is shared, what is different? Core relational themes and expressive displays of eight positive emotions. *Cognition and Emotion*, *27*(1), 37–52.

Carey, S. (2000). Science education as conceptual change. *Journal of Applied Developmental Psychology*, *21*, 13–19.

Carey, S. (2009). *The origin of concepts*. Oxford, UK: Oxford University Press.

Chi, M. T. H. (2005). Commonsense conceptions of emergent processes: Why some misconceptions are robust. *The Journal of the Learning Sciences*, *14*, 161–199.

Chinn, C. A., & Brewer, W. F. (2001). Models of data: A theory of how people evaluate data. *Cognition and Instruction*, *19*, 323–393.

Ekman, P. (1992). An argument for basic emotions. *Cognition and Emotion*, *6*, 169–200.

Foster, M. I., & Keane, M. T. (2015). Why some surprises are more surprising than others: Surprise as a metacognitive sense of explanatory difficulty. *Cognitive Psychology*, *81*, 74–116.

Frazer, J. G. (1998). *The golden bough*. Oxford, UK: Oxford University Press. (Original work published 1922)

Frijda, N. (1986). *The emotions*. Cambridge, UK: Cambridge University Press.

Goetz, T., Frenzel, A. C., Hall, N. C., & Pekrun, R. (2008). Antecedents of academic emotions: Testing the internal/external frame of reference model for academic enjoyment. *Contemporary Educational Psychology*, *33*, 9–33.

Griskevicius, V., Shiota, M. N., & Neufeld, S. L. (2010). Influence of different positive emotions on persuasion processing: A functional evolutionary approach. *Emotion*, *10*, 190–206.

Gruber, M. J., Gelman, B. D., & Ranganath, C. (2014). States of curiosity modulate hippocampus-dependent learning via the dopaminergic circuit. *Neuron*, *84*, 486–496.

Hebb, D. O. (1949). *The organization of behavior: A neuropsychological approach*. New York, NY: John Wiley & Sons.

Izard, C. E. (1977). *Human emotions*. New York, NY: Plenum.

Kang, M. J., Hsu, M., Krajbich, I. M., Loewenstein, G., McClure, S. M., Wang, J. T. Y., & Camerer, C. F. (2009). The wick in the candle of learning: Epistemic curiosity activates reward circuitry and enhances memory. *Psychological Science*, *20*, 963–973.

Kaplan, A., & Maehr, M. L. (1999). Achievement goals and student well-being. *Contemporary Educational Psychology*, *24*, 330–358.

Kashdan, T. B., Sherman, R. A., Yarbro, J., & Funder, D. C. (2013). How are curious people viewed and how do they behave in social situations? From the perspectives of self, friends, parents, and unacquainted observers. *Journal of Personality*, *81*(2), 142–154.

Kay, A. C., Whitson, J. A., Gaucher, D., & Galinsky, A. D. (2009). Compensatory control: Achieving order through the mind, our institutions, and the heavens. *Current Directions in Psychological Science*, *18*, 264–268.

Keil, F. C. (2006). Explanation and understanding. *Annual Review of Psychology*, *57*, 227–254.

Keltner, D., & Haidt, J. (2003). Approaching awe, a moral, spiritual, and aesthetic emotion. *Cognition and Emotion*, *17*, 297–314.

Legare, C. H. (2012). Exploring explanation: Explaining inconsistent evidence informs exploratory, hypothesis-testing behavior in young children. *Child Development*, *83*, 173–185.

Legare, C. H., Gelman, S. A., & Wellman, H. M. (2010). Inconsistency with prior knowledge triggers children's causal explanatory reasoning. *Child Development*, *81*, 929–944.

Linnenbrink, E. A. (2005). The dilemma of performance-approach goals: The use of multiple goal contexts to promote students' motivation and learning. *Journal of Educational Psychology*, *97*, 197–213.

Linnenbrink, E. A. (2006). Emotion research in education: Theoretical and methodological perspectives on the integration of affect, motivation, and cognition. *Educational Psychology Review*, *18*, 307–314.

Loewenstein, G. (1994). The psychology of curiosity: A review and reinterpretation. *Psychological Bulletin*, *116*(1), 75–98.

Lombrozo, T. (2006). The structure and function of explanations. *Trends in Cognitive Sciences*, *10*, 464–470.

Meece, J. L., Blumenfeld, P. C., & Hoyle, R. H. (1988). Students' goal orientations and cognitive engagement in classroom activities. *Journal of Educational Psychology*, *80*, 514–523.

Munnich, E. L., Ranney, M. A., & Song, M. (2007). Surprise, surprise: The role of surprising numerical feedback in belief change. In D. S. McNamara & G. Trafton (Eds.), *Proceedings of the 29th Annual Conference of the Cognitive Science Society* (pp. 503–508). Mahwah, NJ: Erlbaum.

Nersessian, N. J. (1989). Conceptual change in science and in science education. *Synthese*, *80*, 163–183.

Nicholls, J. G., Patashnick, M., & Nolen, S. B. (1985). Adolescents' theories of education. *Journal of Educational Psychology*, *77*, 683–692.

Nolen, S. B., & Haladyna, T. M. (1990). Motivation and studying in high school science. *Journal of Research in Science Teaching*, *27*, 115–126.

Pekrun, R., Elliot, A. J., & Maier, M. A. (2009). Achievement goals and achievement emotions: Testing a model of their joint relations with academic performance. *Journal of Educational Psychology*, *101*, 115–135.

Pekrun, R., Goetz, T., Titz, W., & Perry, R. P. (2002). Academic emotions in students' self-regulated learning and achievement: A program of qualitative and quantitative research. *Educational Psychologist*, *37*, 91–105.

Phelps, K. E., & Woolley, J. D. (1994). The form and function of young children's magical beliefs. *Developmental Psychology*, *30*, 385–394.

Piaget, J. (1971). *Genetic epistemology*. New York, NY: Norton Library.

Pintrich, P. R. (2000). Multiple goals, multiple pathways: The role of goal orientation in learning and achievement. *Journal of Educational Psychology*, *92*, 544–555.

Preston, J. L. (2011). Religion is the opiate of the masses (but science is the methadone). *Religion, Brain & Behavior*, *1*, 231–233.

Preston, J. L., & Epley, N. (2009). Science and God: An automatic opposition between ultimate explanations. *Journal of Experimental Social Psychology*, *45*, 238–241.

Reisenzein, R., Meyer, W.-U., & Niepel, M. (2012). Surprise. In V. S. Ramachandran (Ed.), *Encyclopedia of human behavior* (2nd ed., pp. 564–570). London, UK: Elsevier.

Reisenzein, R., & Studtmann, M. (2007). On the expression and experience of surprise: No evidence for facial feedback, but evidence for a reverse self-inference effect. *Emotion*, *7*(3), 612–627.

Roeser, R. W., Midgley, C., & Urdan, T. C. (1996). Perceptions of the school psychological environment and early adolescents' psychological and behavioral functioning in school: The mediating role of goals and belonging. *Journal of Educational Psychology*, *88*, 408–422.

Rutjens, B. T., van der Pligt, J., & van Harreveld, F. (2010). Deus or Darwin: Randomness and belief in theories about the origin of life. *Journal of Experimental Social Psychology*, *46*, 1078–1080.

Rutjens, B. T., van Harreveld, F., van der Pligt, J., Kreemers, L. M., & Noordewier, M. K. (2013). Steps, stages, and structure: Finding compensatory order in scientific theories. *Journal of Experimental Psychology: General*, *142*, 313–318.

Sagan, C., & Druyan, A. (2006). *The varieties of scientific experience: A personal view of the search for God*. New York, NY: Penguin.

Saroglou, V., Buxant, C., & Tilquin, J. (2008). Positive emotions as leading to religion and spirituality. *The Journal of Positive Psychology*, *3*(3), 165–173.

Sauter, D. A. (XXXX). The nonverbal communication of positive emotions: An emotion family approach. *Emotion Review*, *X*, XXX–XXX.

Schulz, L. E., Goodman, N. D., Tenenbaum, J. B., & Jenkins, A. C. (2008). Going beyond the evidence: Abstract laws and preschoolers' responses to anomalous data. *Cognition*, *109*, 211–223.

Schützwohl, A. (1998). Surprise and schema strength. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *24*(5), 1182–1199.

Seifert, T. L. (1995). Academic goals and emotions: A test of two models. *The Journal of Psychology*, *129*, 543–552.

Shiota, M. N., Keltner, D., & Mossman, A. (2007). The nature of awe: Elicitors, appraisals, and effects on self-concept. *Cognition and Emotion*, *21*, 944–963.

Shtulman, A. (2009). The development of possibility judgment within and across domains. *Cognitive Development*, *24*, 293–309.

Shtulman, A. (2015). How lay cognition constrains scientific cognition. *Philosophy Compass*, *10–11*, 785–798.

Shtulman, A., & Carey, S. (2007). Impossible or improbable? How children reason about the possibility of extraordinary events. *Child Development*, *78*, 1015–1032.

Shtulman, A., & Lombrozo, T. (2016). Bundles of contradiction: A coexistence view of conceptual change. In D. Barner & A. Baron (Eds.), *Core knowledge and conceptual change* (pp. 49–67). Oxford, UK: Oxford University Press.

Shtulman, A., & Yoo, R. I. (2015). Children's understanding of physical possibility constrains their belief in Santa Claus. *Cognitive Development*, *34*, 51–62.

Silvia, P. J., & Kashdan, T. B. (2009). Interesting things and curious people: Exploration and engagement as transient states and enduring strengths. *Social and Personality Psychology Compass*, *3*(5), 785–797.

Sinatra, G. M., Broughton, S. H., & Lombardi, D. (2014). Emotions in science education. In R. Pekrun & L. Linnenbrink-Garcia (Eds.), *International handbook of emotions in education* (pp. 415–436). New York, NY: Taylor & Francis.

Stahl, A. E., & Feigenson, L. (2015). Observing the unexpected enhances infants' learning and exploration. *Science*, *348*, 91–94.

Stiensmeier-Pelster, J., Martini, A., & Reisenzein, R. (1995). The role of surprise in the attribution process. *Cognition & Emotion*, *9*(1), 5–31.

Valdesolo, P., & Graham, J. (2014). Awe, uncertainty, and agency detection. *Psychological Science*, *25*, 170–178.

Valdesolo, P., Park, J., & Gottlieb, S. (2016). Awe and scientific explanation. *Emotion*, *16*(7), 937–940.

Van Schijndel, T. J. P., Visser, I., van Bers, B. M. C. W., & Raijmakers, M. E. J. (2015). Preschoolers perform more informative experiments after observing theory-violating evidence. *Journal of Experimental Child Psychology*, *131*, 104–119.

Vosniadou, S. (1994). Capturing and modeling the process of conceptual change. *Learning and Instruction*, *4*, 45–69.

Webster, D. M., & Kruglanski, A. W. (1994). Individual differences in need for cognitive closure. *Journal of Personality and Social Psychology*, *67*(6), 1049–1062.

Wellman, H. M., & Gelman, S. A. (1992). Cognitive development: Foundational theories of core domains. *Annual Review of Psychology*, *43*, 337–375.