LEARNING TO FEEL LIKE A SCIENTIST

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Affect and the scientific pursuit: Learning to feel like a scientist

Abstract.

This paper argues that affect is central to scientific pursuits and to engaging in science conceptually and epistemologically. To ground this claim, we first review accounts of scientists' intellectual practices that suggest that science involves the activation and refinement of affective resources, such as excitement for figuring things out, annoyance at inconsistencies, empathy with the object of inquiry, and persistence in the face of challenges. We then discuss a case study from a fourth grade science classroom which shows that (1) science learners can experience disciplinary feelings and emotions similar to those of scientists; (2) these affective experiences are closely entwined with the conceptual and epistemological substance of student engagement; and (3) they are consequential to the nature and flow of inquiry. Affect, we contend, is part and parcel of scientific pursuits, and learning science is in part learning how to feel like a scientist. We conclude with some implications of this perspective on research and instruction.

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Introduction

A view of science as a "pursuit"

Educators' ideas and conceptions about the nature of the discipline have significant implications for teaching and research. Science as a discipline is considered to be essentially a pursuit of understanding along with the canonical body of knowledge that results from this pursuit (Hammer, 2004). The notion of a scientific pursuit comprises conceptual content (e.g., ideas, facts, phenomena) and epistemic practices (e.g., argumentation, experimenting, modeling, and seeking coherence). In this paper, we will argue that it also involves affect (e.g., feelings, emotions, dispositions, attitudes, etc.) that is tightly connected to the conceptual and epistemological substance of science.

To show how science involves affect, we first review historical cases of the lives of scientists and studies on disciplinary practices of scientists that point to the centrality of affect in scientific pursuits. We then turn to research on disciplinary learning in science education to argue that attention to affect as substantive to disciplinary practices is lacking from most accounts. Using a case study from a fifth grade science class, we identify affective beginnings in students' engagement that resonate with scientists' experiences and we illustrate the central role of affect in initiating and sustaining student inquiry. We end with some implications related to attending to affect as integral to the disciplinary substance that students should learn and experience in the science class.

The affective substance of scientists' disciplinary practices

While attention to affect in the research community is on the rise (e.g., Damasio, 1994; LeDoux, 1996; Pekrun, Goetz, Titz, & Perry, 2002; Pintrich, Marx, & Boyle; Schwarz & Clore, 2007), research on affect in the domain of science remains relatively scarce for

multiple reasons. First, science has long been considered the epitome of rationality, and a sharp distinction has often been drawn between reason and affect whereby emotions are seen "as a hindrance, a countenance to reason, truth and objectivity" (Alsop & Watts, 2003, p. 1044). Second, the markedly muddled and complex nature of affective constructs poses various conceptual and analytical challenges in defining and studying affect. Third, issues of reliability, replicability, and validity associated with the study of affect through retrospective accounts and self-reporting present multiple methodological concerns. Gruber (2005b) explains that recollections of previous experiences and feelings are constantly perceived and reconstructed through a complex set of filters rather than simply retrieved as experienced (c.f., Bartlett, 1932; Kahneman & Riis, 2005). These and other challenges might have limited research on affect in science, often reinforcing the archetypal image of science and scientists as emotion-free. This view is reinforced by scientists themselves who communicate their work as objective, dry expositions in scientific papers (Medawar, 1963; Ochs, Gonzales, & Jacoby, 1996), which reflects the lingering effects of the "long-standing tradition of […] divorcing and polarizing reason from feeling" (Alsop & Watts, 2003, p. 1044).

However, a careful examination of the intellectual lives of scientists and of learners engaged in disciplinary practices challenges a dry dispassionate portrayal of science. In what follows, we present evidence from case studies on scientists' practices, biographies, and personal reflections that depict the centrality of affect in scientists' experiences, in the creative process of reasoning and problem-solving, and in driving the quest for understanding. We draw on accounts from diverse areas of studies including life sciences, physical sciences, mathematics, etc., to illustrate that feelings and emotions are

experienced in and influence a wide range of intellectual pursuits. Drawing on this wide spectrum might shed light on overlooked affective dynamics in fields that are commonly perceived as devoid from feelings and emotions. We organize the discussion around five themes that depict the nature and role of affect in scientists' pursuits. We note that these themes are our subjective attempt to capture patterns in scientists' affective behaviors and responses; they are neither a comprehensive list of affective experiences nor necessarily indicative of every scientist's experience.

1. *Taking pleasure in phenomena*: this feeling pertains to the experience of excitement and joy in pondering phenomena and forming ideas about the world.
2. *Empathizing with the object of study*: often by embodying a phenomena and identifying with the object of inquiry.
3. *Feeling an idea*: this refers to the "felt knowledge" or the "feeling of cognition" where affect signals an idea or the appraisal of a situation before it is accessible to conscious awareness.
4. *Affective dynamics in collaboration and argumentation*: pertain to emotions experienced while engaging with others and positioning ideas in the community, including peer pressure, insecurity, pride, fear, competition, and so on.
5. *Meta-affect and affective regulation*: this is distinct from the other themes as it speaks to feelings about feelings (similar in many ways to what metacognition is to cognition- deBellis & Goldin, 2006). This involves an awareness and regulation of one's feelings and emotions that enable someone to experience fear as thrilling, challenges as motivating and inspiring, and frustration at inconsistencies as a drive to resolve them.

Below, we discuss each of these themes and their role in the scientific pursuit. Affect, we

argue, infuses scientific practices: it is inextricable from the conceptual and epistemological substance of science, and it motivates disciplinary pursuits.

1) Taking pleasure in phenomena and in figuring things out

Scientists take pleasure in contemplating natural phenomena, and often view science as about uncovering the beauties and mysteries of the universe. Albert Einstein explained that "one cannot help but be in awe when he contemplates the mysteries of eternity, of life, of the marvelous structure of reality" (Einstein, as cited in Miller, 1955), which induces a "deep longing to understand"(Einstein, as cited in Keller, 1983, p.387). Biologist Gerald Edelman spoke of scientists as "kind of voyeurs, they have the splendid feeling, almost a lustful feeling, of excitement when a secret of nature is revealed" (Wolpert & Richards, 1997, p. 137). This "sense of wonder" before the universal mystery as Eisley (1978) described it, is, not surprisingly, a common experience for scientists (e.g., Dawkins 1998; Feynman, 1999; Girod, 2007; Hadzigeorgio, 2012; Keller, 1983; Polkinghorne 1998).

While this notion of excitement and wonderment is prevalent in popular accounts of scientists, here we underscore the importance of recognizing it as part of the work of science. As physicist Carlo Rubbia adds: "We are driven by an impulse which is one of curiosity […]. So we are essentially driven not by, how can I say, not by the success, but by a sort of passion, namely the desire of understanding better, to possess, if you like, a bigger part of the truth" (Wolpert & Richards, 1997, p. 197). Scientists, after all, invest their lives in pondering phenomena and studying the natural world. Keller (1983) describes how the "joy" of phenomena was fundamental in the work of cytogeneticist

Barbara McClintock and gave her “the kind of understanding and fulfillment that others acquire from personal intimacy” (p. 390).

Similarly, Gruber (1974) recounts that, from his early years, Charles Darwin experienced a great pleasure in observing nature and pondering its mechanisms, a pleasure that turned into a passion for his work. Gruber notes that Darwin spent his life delighting in nature's complexity and the web of interconnectedness among organisms. In Darwin's writings, diagrams, and inscriptions, there is strong evidence of feelings and emotions that pervaded his thinking (Gruber, 2005a), suggesting an entangled dynamic of affect and cognition. Gruber concludes that attending to the organization and orchestration of the “affective sensuous components” (p. 132) in Darwin's experience is essential to comprehending Darwin's creativity and scientific reasoning.

In sum, in all these accounts, fascination with the natural world and excitement for forming new ideas and understandings about it, appear to be central to scientists' inquiries and pursuits.

2) Empathizing with the object of inquiry

Various accounts of scientists’ work present evidence of scientists empathizing with the object of their study by identifying it. Virologist Jonas Salk describes how he pictures himself “as a virus or a cancer cell […] to sense what it was like to be either and how the immune system would respond” (Salk, 1983, p. 7). Ethologist Desmond Morris similarly recounts:

> With each animal I studied I became that animal. I tried to think like it, to feel like it. Instead of viewing the animal from a human standpoint—and making serious anthropomorphic errors in the process—I attempted as a research ethologist, to put myself in the animal’s place, so that its problems became my problems. (Morris, 1979, p. 58)

McClintock, Keller (1983) describes, “could write the 'autobiography' of each plant she worked with” (p. 104). She developed a “feeling for the organism” that allowed her to know her corn kernels intimately leading her to formulate her theory of transposable elements of DNA known as “jumping genes." McClintock notes:

> I found that the more I worked with [chromosomes] the bigger and bigger they got, and when I was really working with them, I wasn’t outside, I was down there. I was part of the system… these were my friends … As you look at these things they become part of you. And you forget yourself. The main thing is you forget yourself. (Keller, 1983, p. 117)

This feeling for the object of study, at once affective and cognitive, resonates with patterns identified by Lorimer (2008) in his ethnography on field scientists. Observing and interviewing bird surveyors, Lorimer explains that the field scientists rely on a complex set of affective experiences that helps them “tune in to the bird’s ecology” (p. 377) and gives them a “feel” for the field (p. 384). He recounts that these field scientists experienced a desire to achieve “a form of ‘molecular proximity’ with the chosen organism” (Deleuze & Guattari, as cited in Lorimer, 2008, p. 384).

In another study on physicists’ discursive and representational practices, Ochs et al. (1996) observed that scientists expressed and enacted their involvement “by taking the perspective of (empathizing with) some object being analyzed and by involving themselves in graphic (re)enactments of physical events” (p. 330). Studying the grammatical structures and semantic characters of transcripts from scientists’ discourse during an interaction in a lab, Ochs and her colleagues found that physicists’ utterances were neither exclusively about the scientist him/herself nor about the object of inquiry but rather reflected “a blended identity that blurs the distinction between the two” (p. 339). Several co-occurring linguistic markers reflect such indeterminacy including

pronoun use and verb forms (e.g., “as you go below the first order transition you’re still in the domain structure and you’re trying to get out of it” and “when I come down I’m in the domain state” (p. 339)). Evidence of such referential indeterminacy is further supported by the researchers’ analysis of gestures and graphic representations, suggesting that scientists tend to embody and blend with the object of their inquiry. Moreover, their ability to empathize as implied in the expression “you’re trying to get out of it,” enables scientists to recruit affective resources, such as desire “to get out”, to make sense of and reason about mechanisms. This “capacity for union with that which is to be known” surely reflects “a different image of science from that of a purely rational enterprise” (Keller, 1983, p. 201).

3) Feeling an idea

Various accounts in cognitive and social psychology (e.g., Kahnemnan, 2011; Schwarz & Clore, 2007), neuroscience (e.g., Damasio, 1994; LeDoux, 1996), and studies on scientists and mathematicians’ practices (e.g., Aldous, 2005, 2007; Keller, 1983; Miller, 1992) suggest that ideas are tied to a feeling *within*. This feeling often signals the presence of an idea that is not yet accessible for conscious appraisal. Describing mathematicians' reasoning and problem solving, Burton (1999) remarked that they are often guided by “feelings that are associated with knowing” (p. 134), particularly in states of uncertainty and in “aha” moments:

> These feelings are exceptionally important since, often despite being unsure about the best path to take to reach your objective, because of your feelings you remain *convinced* that a path is there. Such conviction can feed enquiries that go on often over years before a resolution of the problem is completed. (Italicized in original, p. 134)

Einstein described this experience as a "feeling of direction" which guided his thought-experiment leading up to the special theory of relativity: "During all those years there was a feeling of direction, of going straight toward something concrete" (Einstein, 1949, as cited in Keller, 1983, p. 150). In other words, feeling an idea, or the possibility of one, plays a crucial role in guiding the thinking process.

Aldous' (2007) work on expert mathematicians' problem solving reveals similar insights. Analyzing verbal reports of experts engaged in problem solving and their retrospective reflections on their thinking, Aldous observed that participants explicitly referred to feeling an idea, a problem, or a solution, as illustrated in the following examples.

> Some numbers **feel** prime to me. Some answers I get don't **feel** good and those ones usually aren't. (David)
> It was a case in part of trying to determine why my intuitive **feeling** was my intuitive **feeling**. (Eddie)
> I could **feel** it. I could actually **feel** it in my brain. The analysis would take over, and then that would reach a dead end and then I would look for some intuition of where to go. I could **feel** it happening in my head. (Barbara)
> (emphasis in original, Aldous, 2007, p. 182)

These feelings, at once cognitive and affective, are closely associated with a sense of knowing, and suggest the coupling of thought and affect in problem-solving. From this lens, affect pertains to a "feeling of cognition" or a feeling for "a new intellectual order" (Aldous, 2007, p. 181), which forms a kind of information processing that eludes conscious appraisal, leading Aldous (2005, 2007) to conclude that *feeling* an idea is central to its *construction*.

This view is further supported by findings from studies in social psychology that explore affect as a kind of information (Clore, 2009; Schwarz, 2012), as well as findings from neuroscience research (Damasio, 1994; LeDoux, 1996). In his work on patients with

brain lesions that damaged their emotional responses, Damasio (1994) found that, although intellectually unimpaired, these patients were incapable of rational decision-making. Despite their ability to accurately describe positive and negative consequences for their choices, patients were unable to make decisions that optimize their work because they failed to engage emotionally in the process. Damasio thus argued that rather than being an impediment to rational thought, feelings are vital for decision-making and judgment, suggesting the interdependence of affect and cognition. Damasio inferred that "feelings point us in the proper direction […] where we can put the instruments of logic to good use" (1994, p. xiii).

Affect in these accounts refers to feelings that signal the presence of an idea, make it salient, and guide its refinement and development. As succinctly described by Vygotsky (1934/1987):

> [t]hought has its origins in the motivating sphere of consciousness, a sphere that includes our inclinations and needs, our interests and impulses, and our affect and emotions. The affective and volitional tendency stands behind thought. (p. 282)

4) Affective dynamics in the scientific community

Research findings suggest that practices of collaboration and argumentation in a scientific community are often infused with social and affective dynamics that impact knowledge construction (e.g., John-Steiner, 2000; Mahn & John-Steiner, 2002; Plantin, 2004; Thagard, 2008). Thagard (2008) analyzed the role of affect in the collaborative work of Watson and Crick in their discovery of the structure of DNA. He found that the scientists experienced various positive and negative emotions throughout their collaboration, including interest, happiness, sadness, fear, and anger, that can be associated with different stages of their discovery process and their communication with the broader scientific community. For instance, at one point, Thagard recounts, "Watson and Crick

were very worried that the eminent chemist Linus Pauling would discover the structure of DNA before they did, and they also feared that the London researchers, Rosalind Franklin and Maurice Wilkins, would beat them" (p. 240). They felt particularly angry and frustrated at people who impeded the progress of their work or failed to acknowledge them. These feelings drove them to invest relentlessly in their ideas.

Feelings and emotions associated with the broader societal and scientific context often influence scientists' communication with the community. For instance, fear of being rejected or punished for one's ideas, if at odds with dominant views, might impact how scientists share and position their work, at times motivating further care in constructing claims to bolster validity, replicability, and reliability. In the case of Darwin for instance, the worry of society's resistance to materialistic assumptions behind his theory made him reluctant about sharing it (Gruber, 1874). Darwin was, after all, violating the prevailing norms of his religious and scientific context. These and other concerns delayed the publication of Darwin's theory of evolution, initially formulated by early fall of 1837, until the *Origin of Species* in 1859.

John-Steiner (2000) conducted focused interviews with collaborative dyads and small groups of experienced scientists and mathematicians to explore the nature of collaborative environments, complementarity of roles, and motivations in creative collaboration. Participants were asked to sort a list of fifty statements from the most to the least characteristic of the nature and style of their collaboration. Integrating information gathered from interviews and audio-taped commentaries during the sorting task, John-Steiner concluded that the scientists' disciplinary, stylistic, and temperamental differences significantly impact the nature of their interdependence, intimating the role of

affect in the dynamics of collaboration. She also found that collaborations often "provoke intense dialogues and principled disagreements, which can, at times, be daunting" (p. 7). People could become deeply involved in what they say in argumentative situations, experiencing feelings that span from uneasiness, impatience, excitement, irritation, triumph, and anxiety (Plantin, 2004). In partnerships, Mahn and John-Seiner (2002) contend, these dynamics create spaces for "emotional scaffolding" (p. 52) that is crucial for the give-and-take of ideas, constructive criticism, risk taking, and the collaborative construction of knowledge.

5) Meta-affect and affective regulation

In this section, we discuss a distinct kind of affect that pertains to a meta-level (deBellis & Goldin, 2006) - i.e., feelings about feelings and an awareness and regulation of these feelings. While the other themes describe affect with respect to an experience, this theme depicts feelings with respect to feelings, pointing to a certain level of awareness of one's affect. In their reflections, scientists often articulate such awareness or meta-affective dispositions; these might include the recognition of dissonance as motivating and of challenges as thrilling. Scientists often associate puzzles and uncertainties with pleasure rather than intimidation, and perceive inconsistencies as simultaneously bothersome and stimulating rather than menacing. Mathematician Norbert Weiner described discord as a feeling that often motivated his pursuits:

> [O]ne of the chief motives driving me to mathematics was the discomfort or even the pain of an unresolved mathematical discord. I became more and more conscious of the need to reduce such a discord to a semipermanent and recognizable terms before I could release it and pass on to something else. (Weiner, 1956, pp. 85–86)

Likewise, Bertrand Russell remarked: “In all the creative work that I have done, what has come first is a problem, a puzzle involving discomfort” (Russell as cited in Hutchinson, 1959, p. 19). Discord thus creates a sense of discomfort and confusion that drives scientists to improve their current state of understanding. It produces the “aesthetic angst required to motivate the search for a solution” (Root-Bernstein, 2002, p. 72).

To explore how this sense plays out in real-time problem solving, Carlson (2000) analyzed the strategies of twelve research mathematicians who were asked to articulate their thought process as they engaged in mathematical tasks. Participants were later asked to reflect on their problem solving experience. Analyzing these data sources, Carlson observed that during problem solving attempts, “each mathematician exhibited mild frustration; However, their high confidence and use of coping mechanisms appeared to mitigate adverse affects” (p. 143). “It was during these frustrating moments,” Carlson notes, “that they were most frequently observed scanning their knowledge base” (p. 143). Most notably, Carlson recounts, mathematicians had “internal discussions” to manage various cognitive and emotional responses to the problem-solving situation and were unwilling to let go of a problem once they had initiated a solution. They even kept at the problem after the interview had ended. These case studies highlight a kind of meta-affect whereby frustration at “not knowing” is leveraged to stimulate and inspire thinking.

Along these lines, interviewing scientists and mathematicians, Firestein (2012), a practicing scientist himself, found that scientists identify incompleteness and uncertainty as opportunities to try out new ideas, pose new questions, and grapple with the unknown. "Mucking about in the unknown,” Firestein remarks, “is an adventure; doing it for a living is something most scientists consider a privilege" (p. 15). Despite the possibility of

finding out "that they were pitifully mistaken, fundamentally incorrect," (p. 66) grappling with the unknown generates "the motivation, the excitement, the thing that gets you to the lab early and keeps you there at night" (p. 66). From these cases and his own experiences, Firestein concludes that "[s]uccess in science, either doing it or understanding it, depends on developing comfort with ignorance" (p. 87).

These findings suggest that being a scientist requires the cultivation of productive affective dispositions toward intellectual discomfort and uncharted knowledge terrains. Gruber (2005b) describes two stances that people might take in this regard:

> Someone could begin to have a dangerous idea and feel that he was going in a dangerous direction before he had the thought quite formulated. He could even decide to discontinue it, or simply veer away from it the way one does from danger while driving a car [...]. Another person, with a different style, could rush toward the idea precisely because in embryo it felt dangerous, exhilarating. (p. 203-204)

Scientists seem to reflect the latter stance, and part of learning science, we argue, is learning how to *feel* like a scientist, by developing productive dispositions toward uncertainty and risk. Experiencing the unknown as enticing, transforming fear and frustration into "interesting, curious, even euphoric" experiences, anticipating "elation at understanding something new or achieving a difficult goal" (deBellis & Goldin, 2006, p. 137), are affective stances that, we contend, can be nurtured and cultivated in the science class as we elaborate later in this paper.

Summary

Merton (1973) notes that "[a]lthough it is customary to think of the scientist as a dispassionate, impersonal individual, it must be remembered that the scientist, in company of all other professional workers, has a large emotional investment in his way of life" (p. 259). The review above presents compelling evidence to challenge dry

impersonal portrayals of scientists. We identified five themes pertaining to affect in scientific pursuits, including (1) Taking pleasure in phenomena; (2) Empathizing with the object of study; (3) Feeling an idea; (4) Affective dynamics in collaboration and argumentation; and (5) Meta-affect or affective regulation. This review shows that scientists' intellectual trajectories are infused with affect that is essential to advancing intellectual pursuits. It thus supports a synergistic account of affect and cognition and motivates the construal of affect as inherent to the discipline of science.

From scientists' practices to classroom teaching and learning

Now that we have provided evidence of affect as part and parcel of scientists' work, how can this insight inform our thinking about science teaching and learning in the context of the classroom? To address this question, we need to consider what happens in the science class. Traditionally, science classes are designed around scripted lesson plans and learning objectives, predetermined by the teacher and the curriculum. These classes rarely leave room for children's own questions and wonderment, and for opportunities to experience science as a pursuit. Burton (1999) refers to a chasm between the transmission pedagogy prevailing in the traditional schooling system and the "perspective of coming to know" (p. 135) as experienced by scientists in their inquiries; and a corresponding chasm between students' "language of 'boring' " and "the language of fun, of 'euphoria', of excitement, of personal struggle and achievement" (p. 135) of practicing professionals.

Recently, however, researchers are drawing attention to the importance of engaging students in practices that align with the discipline (e.g., Ford & Forman, 2006; Lehrer, 2009; NRC, 2011). There is a call to design instruction around an *epistemic culture* (Knorr-Cetina, 1999) that fosters students' agency and engagement in practices

recognized by the scientific community (e.g., Driver, Newton, & Osborne, 2000; Engle & Conant, 2002; Ford, 2008; Hammer, 2004; Lehrer, 2009, Scardamalia, 2000, 2002). This line of research provides a vital foundation for framing science education by stressing that students should encounter science in ways that support disciplinary understandings and disciplinary dispositions.

While we align with this call, we argue that attention to affect as part of the discipline has been lacking. In what follows, we review some work on disciplinary learning in science and we shed light on affective dynamics that students experience when they encounter science as a pursuit. Attending to affect within disciplinary practices, we contend, opens up new ways of thinking about instructional design and research in science education.

Research efforts to promote disciplinary learning and engagement in science

Moving beyond treating science as a body of knowledge, reform instruction underlines the need to promote and refine student inquiry practices and critical ways of thinking to support scientific understandings of the world. Accordingly, researchers have focused on understanding students' engagement in and awareness of aspects of inquiry, such as argumentation, generation and assessment of ideas, and pursuit of causal coherent understandings (e.g., Driver, et al, 2000, Engle & Conant, 2002; Ford, 2008; Hammer, 2004; Kuhn, 1991). Engle and Conant (2002) suggest some principles to guide the design of classrooms that offer students opportunities to problematize knowledge claims and become intellectual authors in their learning. Likewise, Ford and colleagues (Ford, 2008; Ford & Forman, 2006; Ford & Wargo, 2007, 2012) discuss "authentic engagement" in science as the "grasp of practice." They argue that when in contact with the disciplinary

practices of generating and critiquing ideas, students develop a sense of what scientists actually do as they put forth knowledge claims and assess their epistemic status. Scardamalia and Bereiter (1991, 2006) discuss the need for designing pedagogy that promotes students' intentional learning and "epistemic agency," where learners can take charge of the knowledge-building process. Students as epistemic agents, the authors argue, initiate questions, monitor strategies, assess goals, collectively create and refine knowledge artifacts, and negotiate a fit between their own thinking and that of others (Scardamalia, 2000, 2002). Meaningful engagement in science is further promoted in classes that encourage a heterogeneity of voices and that allow diverse ways of knowing interact and populate the discourse, as Warren and colleagues contend (Rosebery et al., 2010; Warren, et al, 2001; Warren, Ogonowski, & Pothier, 2005). These researchers problematize the dichotomy between "everyday experience" and "scientific thinking and knowing," arguing for the need to support students' own ways of reasoning and interacting with the world. This line of work views students' conceptual, linguistic, and epistemological resources as affordances rather than impediments to their learning, and as continuous with rather than oppositional to scientific practices.

However, most of the emphasis in this research on disciplinary learning concerns science as a conceptual and an epistemological experience. Here, we foreground the affective dimension of this experience. As they engage in science as a pursuit (rather than as a body of knowledge to be learned), students activate affective resources similar to those of scientists: They become driven by their questions; they feel compelled to find explanations and to confirm ideas; they recognize their frustration at inconsistencies and

feel the urge to reconcile them. In brief, they experience the drives and motivations of scientists in their pursuits.

To be sure, various accounts in the literature attend to affect in student learning, however most of these accounts consider affect as evidence of or an outcome from student engagement, not at the core of understanding and conceptualizing student disciplinary learning. Here, we propose a distinct move: that affect is inherent to the disciplinary substance that students need to learn in the science class. Learning science, we contend, is in part learning how to *feel* like a scientist. Looking across a range of richly-described case studies of student inquiry in the literature, we notice that affect, often considered a marker of student engagement, is tightly coupled to students' sense-making efforts. For instance, in Engle and Conant (2002), 10-year-old students became passionately engaged in solving the challenge of classifying orcas as dolphins or whales. They felt compelled to figure out a way to sort out and evaluate sources of information, and to reconcile their intuitions with the information presented to them. Students' affect, sparked and animated the debate: their curiosity about the question, their enjoyment of the ownership of the orca challenge, and their joy and excitement at formulating arguments to address it, seemed substantive to the nature of their engagement and to holding each other accountable to disciplinary norms. These disciplinary feelings and drives, we argue, are integral to experiencing science as a pursuit, and students need to recognize them as inherent to the doing of science.

In addition to research on student engagement, evidence of affect pervades practitioners' reports on their teaching. Examples include Hammer's (1997) analysis of his own physics teaching and Duckworth's (2001) description of teaching density.

Though not foregrounded in Hammer's (1997) paper, issues of affect including students' motivation, their delight in coming up with theories and explanations, teacher's frustration, and classroom mood, permeate the discussion. Duckworth (2001) explicitly reflected on affect as the driver of student inquiry in her teaching of density:

> The work was characterized as much by feeling as by ideas. Playfulness, mystification, laughter, excitement, frustration, trust, confusion, fascination, determination, appreciation of visual beauty, enjoyment of one another--all of these were involved in keeping the work going. (Duckworth, 2001, p. 39)

These documented cases, as well as the case study we analyze later in this paper, suggest that affect is not only evidence for or an outcome of student engagement, but it is rather integral to learning science. It is part of the disciplinary substance that students should experience and learn in the science class. As Brown and Walter (1990) point out: "It is because we are surprised, puzzled, or confused by an approach we have taken or a conclusion we have reached that we feel compelled to ask a new set of questions" (p. 65). Asking questions is central to science and is largely motivated by confusion or surprise; argumentation and problem-solving are the means to pursue questions and are often driven by frustration and confusion, and by anticipating the joy of a resolution or an understanding.

In the rest of the paper we present our case-study from an elementary science classroom that shows how, when engaged in their own pursuits, students experience affective dynamics that resemble those of scientists, and that are consequential to the nature of their engagement. We then discuss implications for considering affect as integral to the disciplinary substance of student inquiry in research and instruction.

Data sources and context of study: the Learning Progression project

The case study we present is from a three-year National Science Foundation funded project on learning progressions for scientific inquiry[1]. The Learning Progression (LP) project involved curriculum design, professional development, and research on student and teacher learning. The project is designed to promote practices of "responsive teaching," or teaching centered on recognizing, interpreting, and responding to the substance of student thinking (Coffey, Hammer, Levin, & Grant, 2011; Hammer, Goldberg, & Fargason, 2012). The goal is to help learners experience science as a pursuit by focusing on their own ideas and lines of inquiry. The project staff supported teachers to develop practices of responsive pedagogy by engaging them in science talks, reflective discussions, and analysis of artifacts of practice including classroom videos and student work. All of the teachers implemented responsive teaching "modules" that comprise a launching question designed to elicit rich student thinking. Most of the ideas and questions that the students discussed were not a priori scripted by the teacher or the curriculum, and often the teacher did not have ready-made answers to students' questions, creating situations similar in some ways to what scientists encounter in their pursuits.

Data Analysis

Video analysis of classroom interactions: A multimodal approach to analyzing affect

While surveys and questionnaires are often used as research instruments to study affect (e.g., Glynn & Koballa, 2006; Pekrun, et al., 2011), in this work we use video analysis to explore affect as it plays out in classroom interactions (Derry, et al., 2010;

Goodwin, 2007; Jordan & Henderson, 1995). Videos are a tool to explore affect in a more organic and naturalistic way, especially in moment-to-moment dynamics. Our analysis comprises classroom episodes that show evidence of rich student engagement as reflected by the content of the discussion (student ideas and questions) and the epistemic practices (generating questions, justifying claims with evidence, identifying inconsistencies, suggesting experiments to test ideas, etc.). For space concerns, we limit our analysis here to one case study of fourth graders discussing clouds.

We adopt a multi-modal approach (Stivers & Sidnell, 2005) to identify verbal and non-verbal markers of affect in action, as expressed and organized through stances embedded within the flow of the activity (Goodwin, Cekaite, Goodwin, & Tulbert, 2011). These markers might include: explicit discursive indicators (e.g., "YAY!"; "That would be awesome"); paralinguistic markers including prosody (e.g., intonation, raised and lowered voice, speech stress, overlapping and oppositional speech, exclamation or questioning tone, cut-offs); and physical displays (e.g., gestures, hand movement, facial expressions, body positioning, motion such as standing up or jumping).

Classroom episode: "How does a cloud hold water?"

The case study we analyze is a ten-minute episode from Mr. Myers' fourth grade science class discussing clouds. This episode represents, from the teacher's perspective and ours, a shift in students' participation that the teacher had been trying to achieve: the students taking up inquiry among themselves without his direct involvement. In brief, a group of 18 fourth-graders were sitting with their teacher in a circle on the floor discussing clouds. Their conversation began with the usual routine the teacher had been trying to change, of students speaking to him rather than to each other. At the beginning of the episode, a

student Alyssa was explaining how clouds get water. Addressing the teacher, Alyssa describes “that water comes from the air that has always been there.” She adds that the more the cloud collects water, the darker and heavier it becomes; and when the cloud can’t hold any more water, it starts to rain. Jordan raised her hand, and the teacher called on her. She started to express her agreement with Alyssa but spontaneously cut herself off:

1. Jordan: Um, I think. I agree with Alyssa, because if a cloud- well - I have a question.[1]
2. Mr. Myers: Ok.
3. Jordan: What's in a cloud that makes it hold the water?
4. Alyssa: (to Jordan, very low voice): it just does it.
5. Jordan: Like, does it float?
6. Mr. Myers: Oooo I see a scrunchy face (looking at Brian). What are you thinking about? Did you listen to her question?
7. Mr. Myers: Could you say your question one more time Jordan?
8. Jordan: Why does- how could water be in a cloud without falling? (Silence)

Instead of elaborating on her agreement, Jordan interrupted her statement to pose a question about a mechanism that seemed to puzzle her: before discussing the details of water getting into a cloud, we need to establish how the cloud can hold water in the first place! Jordan asked her question in a soft-spoken, hesitant voice, facing the teacher. Mr. Myers acknowledged her question and encouraged students to consider it. Students’ initial responses, however, did not seem to address Jordan's inquiry. Jordan suggested a possible way for a cloud to hold water, namely if the water in the cloud was a gas that changes into liquid when it rains:

[1]Transcript notation: Capitalized words refer to emphasis or stress in the speech; Two open brackets [on different turns refers to overlapping speech; = refers to latching; [text] refers to inaudible meanings or words; (text) describes paralinguistic aspects of the interaction.

9. Jordan: I think if it could [hold water], it would be gas that would be in the cloud and the water has already turned into gas. So when it falls out, something happens in it, and it gets back to water.

Up until this point of the conversation, evidence of affect was relatively subtle. Students participated in a similar mode as before, still speaking to the teacher. Some students responded to Jordan's puzzle suggesting for instance that the cloud does not actually hold water, or that "it is so light." The teacher asked Jordan to reiterate her question; directly after that, Alyssa raised her hand to repeat her initial idea about the water cycle emphasizing that the cloud holds "as much as it can" and then drops the water as rain:

10. Alyssa: It gets the water- well it can hold as much as it can (Jordan drops her hands to the floor and beats them on the carpet in disappointment) and then it turns to grey and then and then it just drops it and that's when it rains, but uh-

At this moment, Jordan interrupted her with the same question, this time with greater intensity: "But what holds it?" posing her question for the third time, speaking with a loud voice and with her two palms upturned. Alyssa replied, "the cloud!", looking serious at first but ending with a smile (Figure 1). Jordan then became more animated and asked her question again with a marked change of tone and pace, vivid gestures, and now facing her classmates. She exclaimed that the cloud does not have "a magical wall" to hold the water without it dropping.

11. Jordan: But- what holds it? (Figure 1)
12. Elea: Yeah! How does it hold it?
13. Alyssa: The clooood!
14. Jordan: (Palms upturned) HOW? (Figure 2)
15. Elea: Yeah HOW?
16. Jordan: How does a cloud hold it? It doesn't HAVE a magical WALL holding it!

17. Elea: Yeah (laughing) like- it doesn't have a patch under the cloud so like to keep the water in!
18. Alyssa: (in a lower voice and looking down) It just holds as much as it can. (Figure 3)
19. Jordan: HOW=
20. Elea: How can it hooooold IT!?
21. Jordan: =without a WALL or a PATCH under it!?
22. Alyssa: (smiling, looking down)
23. Jordan: Does it like turn into gas? what does it do?
24. Elea: (laughing)

Figure 1. Jordan (in the black shirt) begins to challenge Alyssa.

Figure 2. Jordan is getting feisty.

Figure 3. Jordan is dissatisfied with Alyssa's response and doesn't abandon her question.

We note several aspects of this exchange: First, Jordan was curious about what keeps water in the cloud, a phenomenon that puzzled her. Her confusion and puzzlement about the cloud phenomena drove her to persist at the question as evidenced by her pushing back against Alyssa's response. Jordan recognized that Alyssa's response did not address her inquiry. Her reaction to this epistemological discord was intense: her demeanor shifted from being calm and soft to becoming increasingly animated and assertive as evidenced by her gestures and facial expression (palms upturned and discontented look on her face); she became significantly louder and feisty as reflected by her prosody (tone and pitch) and her ironic use of the word "magical."

In response to Jordan's heightened affect, Alyssa smiled. While it is impossible to know for sure the meaning of her smile, a plausible interpretation is that Alyssa sensed a tension from Jordan's reaction and thus smiled as an attempt to release tension and save face. Evidence of this tension became clearer as the discussion unfolded: in a sudden move, Alyssa pushed away from Jordan shielding herself with her arm held up (Figure 2)

then scrunching her shoulders with her hands held down together tightly (Figure 3), looking down, and lowering her voice as she utters: “it just gathers as much as it can.”

In this excerpt and in what follows, we speculate that Jordan was not simply expressing emotions to vent and feel better; she was voicing her frustration as a way to communicate her assessment with respect to the nature and content of the conversation (Schwarz, 2012), namely that the discussion was not addressing her inquiry. In these ways, Jordan’s intensified expression and emotional display were doing some work for her at an epistemological level. The shift in Jordan’s tone of voice, gestures, and ways of speaking all seemed to signal to her classmates (and to us as analysts) that she has entered a new kind of framing dynamic (Tannen & Wallat, 1993). In effect, Jordan’s register changed from that of a demure, compliant student seeking the teacher’s consent to that of an epistemic authority acting and speaking with assertiveness, and evaluating the quality of her peers’ contributions; she is in this moment a nascent scientist seeking to understand.

We are not claiming that Jordan is necessarily conscious of her role and the shift in framing that she initiated. In our discussion about scientists, we explored how an internal feeling could signal substantive conceptual and epistemological information eluding the scientist’s consciousness; here, by externalizing her feeling, Jordan leveraged it as a tool to communicate her thinking to others. This interpretation is further supported by evidence from Elea’s response to Jordan’s puzzlement who exclaimed: “yeah! How does it hold it,” laughing at Jordan's “magical wall” comment signaling her agreement that the class has not provided a compelling mechanism that explains how the cloud holds water.

Right after this exchange, another student whispered a response to Jordan's question, namely "low gravity." Jordan however quickly problematized this explanation arguing that gravity cannot explain how water is held in the cloud for this contradicts the fact that rain falls down:

25. Jordan: So how does it hold it?
26. Kyle: Low gravity
27. Elea: Low gravity?
28. Jordan: It's not gravity coz water can't go [down] without gravity!

Figure 4. Jordan questions Kyle's idea.

As we mentioned at the beginning of this section, the teacher had been struggling to change the classroom norm of conversation- of students addressing him rather than directly engaging with each other. In this episode, Jordan started addressing her classmates directly without reaching to Mr. Myers first as the authority or the moderator of the discussion. These behaviors mark the beginning of a shift in the classroom participation patterns that, soon enough, spreads across the room. In effect, more students took up Jordan's tone and pace, as well as the pattern of speaking to each other. Anchored

in her deep puzzlement about how clouds hold water, Jordan's affect, we contend, was the trigger for this shift.

Silently attending to this exchange, Mr. Myers, smiling, interrupted the conversation to express his satisfaction with how students were engaging with each others' ideas without him facilitating the discussion. He noted that this was something he had been trying to achieve for some time, and invited the class to include more students in the discussion. One could imagine that Mr. Myers' interruption and long speech turn (1min, 46s) might have disrupted the flow of the discussion and that students might have become distracted from the "cloud puzzle," a worry that some of the researchers in our group expressed as they watched the clip; interestingly however, soon after Mr. Myers' remark, a short moment of silence ensued and the conversation picked up again with the same feistiness and vigor.

As Alyssa stated for another time her description of how water from the air gathers in the clouds and comes down in the form of rain, Jordan interrupted her in an oppositional stance pointing out that Alyssa's reasoning did not address the question:

29. Alyssa:	It gathers the water from the air and then it gets as much as it can and then it drops it and then it turns black
30. Jordan:	I don't understand, because she says it gathers all the water!
31. Jordan:	HOW?
32. Alyssa:	It sucks it uuup!
33. Jordan:	(turning to Alyssa) How does it HOLD it though? That's the question-
34. Elea:	It is really light-
35. Jordan:	Not how does it go up-
36. Student:	Maybe the water is very light
37. Jordan:	How does it hold it!

Jordan became more adamant about her “how” question: in this short exchange, she restated the question three times (see lines 31, 33, and 37). Jordan was also taking agentive roles to redirect the discussion toward her question by explicitly commenting on the nature of the question to clarify what kind of conversation should take place here: “that’s the question, not how does it go up,” and a little later noting: “This is not the question, the question is how does it hold it.” She also evaluated her classmates’ contributions with explicit epistemological comments such as: “that doesn’t make sense.”

As the conversation continued, the substance of the students’ utterances became more focused on the question around mechanism that Jordan originally raised, including suggestions of plausible explanations. Again, Kyle brought up the idea of gravity, reasoning that “the higher up in the sky, there's not a lot of gravity. So the clouds are very high so it's just floating up there.” Jordan, still not convinced, expressed her dissatisfaction in an intense and persistent manner: “HOW does it float?,” “HOW CAN IT float?” and, turning to Kyle, she said in disappointment: “That doesn't make sense,” a point she had argued previously with her observation that if gravity holds the water in the cloud, then it would not be possible for rain to fall down. Little by little, students across the room aligned themselves with Jordan's reasoning and conversational style. Noticing multiple budding side conversations, Mr. Myers suggested that students pair up to continue the discussion:

38. Mr. Myers: I 'm hearing a lot of like little conversations that I want you guys to honor, so, what I want you guys to do is that I want you to turn to your neighbor, and I want you and your neighbor to talk about this idea-

Figure 5. Jordan and Alyssa hold hands smiling.

At the end of Mr. Myers' comment, Jordan turned toward Alyssa and gave her a high five. The girls held each others' hands, smiling (Figure 5). Jordan might have felt Alyssa's tension when she was challenging her ideas and, possibly as part of responding to Alyssa's affect, Jordan amicably turned towards her offering a high five as a way to check in that there were no hard feelings. Additionally, as reflected by their smiles, the girls seemed to be experiencing a moment of accomplishment and a sense of pride as a result of taking ownership of the conversation and expressing their ideas freely. The affective dynamics in Jordan and Alyssa's interaction on one hand reflect various tensions associated with argumentation and on the other show signs of the joy in the "having of ideas" (Duckworth, 2006) and in taking agentive roles to pursue them.

Informal debriefs and interviews with Jordan provide further support for the claim that she indeed took pleasure in the give-and-take of ideas and the opportunities for self-expression. Almost four months before this focal episode, Jordan explained in an interview that she enjoyed science class because students "have more chances of saying what we think and imagine." In another interview just a few days before this episode, Jordan described how she enjoys the space for ideas and argumentation that she gets to experience in Mr. Myers' class:

Jordan: In [Mr. Myers's] class, I like that we don't have to use a science book and we get to talk to each other, get our ideas out, and we get to listen what other people think of, and we could disagree and agree with them, so that's pretty cool.

In brief, in this episode, Jordan's motivation to pursue her question and her frustration with the offered responses made her recruit various tools to engage the class in ways that would address her inquiry. These included her strong affective displays as well as her epistemological remarks regarding the nature of the conversation. Jordan's heightened affect and animated communication suggest that she was annoyed and frustrated, but refused to let go of her inquiry. These feelings and emotions reflect aspects of Jordan's "disciplinary affect" (Jaber & Hammer, under review): being curious about phenomena, getting annoyed at dissatisfactory explanations, keeping at a question, and persisting in the face of challenges. These affective responses, we have argued, are prevalent in scientists' practices. McClintock, for instance, when surprised by unanticipated results in the corn field, became disturbed "so much so that she left the field, down in the hollow, and walked up to her laboratory. There she sat for about thirty minutes, just thinking about it" (Keller, 1983, p. 104). We see signs of such disciplinary drive in Jordan's reactions. Additionally, in Jordan's case, her affect soon spread across the room, initiating and sustaining a local coherence of "disciplinary motivation" (Jaber & Hammer, under review) in the class.

Moreover, as they further engaged in argumentation, students experienced various affective dynamics in positioning their ideas in class. These included the worry of being judged or misunderstood, and affective tensions associated with challenging each other's ideas, as evident in the interactional dynamics between Jordan and Alyssa. Other affective dynamics included the joy and excitement in formulating and expressing ideas

freely and the feeling of accomplishment and pride in taking ownership of the conversation. As we have shown, these feelings and emotions are often part of scientists' experience as they converse and interact with a community of scientists. The evidence from this case study suggests that, when they encounter science as a pursuit, children also show and experience emotions and drives similar to those of practicing scientists, reflecting the emergence of their disciplinary affect.

Finally, in this activity, the class entered a mode of conversation among students where they became the main animators and owners of the inquiry. We notice a shift in the nature and substance of the activity, evident in the change in participation patterns as well as in the content of what students discussed. We contend that this shift is largely affective in nature: Jordan's initial question came out of her curiosity about mechanism - how can an airy cloud "hold" liquid water? She saw her question as about mechanism but recognized that others did not align with her epistemologically, which made her more vigorous and direct in posing the challenge, "forgetting" and shifting away from the tacit and previously established social rules of engagement - that students speak to the teacher. Thus experiencing a puzzle and being driven to solve it triggered and stabilized the shift to a new dynamic of student participation.

Conclusion and Implications

"Science," Sacks (2004) contends, "is far from being coldness and calculation, as many people imagine, but is shot through with passion, longing and romance" (p.1 5). We have argued with compelling evidence that affect is inherent to scientific practices using cases from scientists and from students engaged in inquiry. Our purpose was to identify how engaging in science is not exclusively conceptual or epistemological in

nature, but that it also entails an affective involvement. Using a case study of student "productive disciplinary engagement" (Engle & Conant, 2002), we illustrated the integral role of affect in student inquiry. We argued that: (1) when children experienced science as a pursuit, they showed beginnings of disciplinary affect that resembled scientists' affective experiences such as curiosity about natural phenomena, frustration with dissonance, persistence in the face of challenges, and joy at formulating ideas; (2) their affect was closely entwined with the epistemological and conceptual substance of the inquiry; i.e., students' feelings and motivations were entrenched in the science "puzzle" or question that intrigued them; and (3) affect was central to initiating and sustaining students' inquiry and their framing the science activity as a sense-making pursuit. As such, we contend that feelings and emotions experienced *within* the work of science are inextricable from the conceptual and epistemological substance of science and motivate its development.

In terms of instruction, this perspective intimates the need to attend and respond to students' affect within science to promote their "disciplinary engagement" (Engle & Conant, 2002) and "epistemic agency" (Scardamalia, 2000, 2002). In order to experience science as a pursuit, students must encounter a range of emotions and feelings that scientists experience in their quest for understanding, including uncertainty, frustration, curiosity, fascination. Here, it is important to consider an area of affective learning that targets feelings about feelings and the ability to regulate one's feelings and emotions as an important part of doing and learning science. The notion of meta-affect (deBellis & Goldin, 2006) can prove powerful to support such learning. In that, educators must help students "befriend" intellectual discomfort through creating opportunities for productive

struggle and through engaging in explicit conversations about feelings and emotions in the intellectual work of science.

To refine students' meta-affect, educators should aim to foster "supportive classroom culture [that] provides a sense of safety in being 'stuck'" (deBellis & Goldin, 2006, p. 137). Teachers can help students come to associate challenges with pleasure, to experience inconsistencies as motivating, and not to give up in the face of a thorny problem. They also can play a role in helping students indentify for themselves the specific and perhaps personal feelings that "keep them going," and how they can leverage these feelings productively to achieve intellectually satisfying accomplishments. The goal is "*not* to eliminate frustration, remove fear and anxiety, or make [scientific] activity consistently easy and fun" (deBellis & Goldin, 2006, p. 137, emphasis in original) but to help students develop comfort with feelings associated with difficulties, and foster a sense of anticipation for constructing an understanding. In this way, affect becomes part of what science teaching must explicitly attend to and plan for in classes that offer spaces for students' own questions and inquiries.

Lastly, it is worth noting that we have mainly focused in this paper on the constructive aspects of affect underpinning disciplinary engagement. To be clear, we surely do not consider that the affective dynamics identified here as integral to science are always productive. Affect, after all, can at times hinder and bias one's engagement and critical thinking, and can potentially skew the thinker toward a perspective without the prudent examination of its validity. Being strongly attached to one's belief, idea, or theory, or being affectively influenced by the social or political status of a person or a group of people behind an idea, can lead to funneled vision and lack of openness to

alternative perspectives. Thus, rather than considering affect as good or bad in and of itself, we understand its productivity in light of how, when, in what ways, and for what purposes, it is activated and employed.

In other words, rather than attaching unitary attributes to particular affective dispositions, considering affect as a set of resources within a cluster of conceptual and epistemological resources help us appreciate the context sensitivity of its quality and productivity (Elby & Hammer, 2001). Here are some examples to illustrate: while being attached to one's idea in order to develop it is a perfectly legitimate stance to take at some stages of inquiry, it might become unproductive at others, for instance when more promising and better supported ideas become available; keeping at a question is essential to initiate and drive inquiry but it might become fruitless and wasteful when more pressing questions need attention or when various technological or material challenges make the pursuit impossible at the time.

The examples above point to the importance of developing and refining one's meta-affect: as learners become aware of how their affect constitutes and drives their engagement, they can develop nuanced ways of regulating and interpreting their feelings. Noticing one's overzealous excitement for an idea for instance can become a signal to motivate further care in supporting the idea and constructing arguments to bolster validity and reliability. Thus, we stress that, as foundational to the discipline, affect should not be approached in a sentimental or a prescriptive manner. Affect, we contend, must be examined and appreciated in the specifics of its context, within the cluster of conceptual and epistemological resources that, in union with affective resources, constitute the discipline of science.

Endnotes

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