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Critical thinking during science investigations: what do practicing teachers value and observe?

Kirsten R. Butcher ^a, Michelle Hudson^a, McKenna Lane^b and Madlyn Larson^c

^aDepartment of Educational Psychology, University of Utah, Salt Lake, UT, USA; ^bDepartment of Curriculum and Instruction, University of Illinois, Urbana, IL, USA; ^cEducation and Community Engagement Department, Natural History Museum of Utah, Salt Lake, UT, USA

ABSTRACT

This paper examines how practicing teachers approach and evaluate students' critical thinking processes in science, using the implementation of an online, inquiry-based investigation in middle school classrooms as the context for teachers' observations. Feedback and ratings from three samples of science teachers were analysed to determine how they valued and evaluated component processes of students' critical thinking and how such processes were related to their instructional approaches and student outcomes. Drawing from an integrated view of teacher practice, results suggested that practicing science teachers readily observed and valued critical thinking processes that aligned to goal intentions focused on domain content and successful student thinking. These processes often manifested as components of effective scientific reasoning—for example, gathering evidence, analysing data, evaluating ideas, and developing strong arguments. However, teachers also expressed avoidance intentions related to student confusion and uncertainty before and after inquiry-based investigations designed for critical thinking. These findings highlight a potential disconnect between the benefits of productive student struggle for critical thinking as endorsed in the research on learning and science education and the meaning that teachers ascribe to such struggle as they seek to align their instructional practices to classroom challenges.

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Introduction

Critical thinking frequently is cited as a key goal of formal instruction, with critical thinking serving as a foundation for 21st century workers and global citizens to make meaningful contributions to society (Halpern, 2014; Partnership for 21st Century Skills, 2009). Because scientific evidence increasingly serves as an important source of data to inform individual actions and community decisions, science education has been highlighted as a particularly important context for developing effective critical thinking skills. Critical thinking in science sets the stage for learners to become savvy consumers of information in the modern world (Halpern, 2014; Vieira & Tenreiro-Vieira, 2016). But

little is known about how teachers approach critical thinking in science instruction, or how they observe and evaluate its implementation in their classrooms. If our goal is to support the development of effective critical thinking in science education, we first must understand what practicing teachers intend to do in their instructional practices and how they interpret what they see in their classrooms as critical thinking unfolds.

Uncertainties in how critical thinking manifests during learning are not limited to science education. Researchers disagree about whether critical thinking represents a unique but generalisable set of cognitive skills (Kuhn & Pease, 2008; Kuhn, 2009) or if critical thinking is constrained by domain-specific approaches to inquiry (Brown, 1997). Reflective of this overarching disagreement, some researchers have defined critical thinking as a broad set of thinking strategies that reflect generally desirable characteristics—for example, ‘reflective and reasonable thinking that is focused on deciding what to believe or do’ (Ennis, 1985, p. 45) or ‘thinking that is purposeful, reasoned, and goal directed’ (Halpern, 2014, p. 6). Other researchers have emphasised an approach to critical thinking that focuses on the interaction between the cognitive processes of learners and the information upon which those processes can operate. For example, Kuhn (1999) characterised critical thinking as (developmentally appropriate) cognitive processes that operate on empirical evidence. Defining critical thinking in the context of cognition and evidence is well-aligned to science instruction, as reformed approaches to science education emphasise the critical importance of strategic and reflective student thinking about evidence that is derived from phenomenon-centred learning (Lee et al., 2004; Penuel et al., 2019). Thus, this paper adopts Wentzel’s (2014) definition of critical thinking as ‘an effortful and deliberate cognitive process that entails reflection on and evaluation of available evidence’ (p. 579). Accordingly, critical thinking during inquiry-based science learning should be evident in the component cognitive processes that are deployed as students gather and analyse evidence, consider multiple ideas or explanations based on patterns of evidence, and develop well-supported, evidence-based arguments. This paper examines students’ critical thinking processes in science from a teacher perspective, focused on two key research questions:

RQ 1: How do practicing teachers conceptualize and approach critical thinking skills as they prepare to teach an online, inquiry-based science investigation?

RQ 2: What do practicing teachers observe and value about students’ critical thinking processes following completion of an online, inquiry-based science investigation?

An integrated approach to instructional practice

An integrated approach to instructional practice recognises that teachers’ pedagogical actions in the classroom are driven by multifaceted concerns about domain concepts, students’ cognitive and emotional processes, the realities of classroom teaching, and teachers’ own desires, needs, and constraints (Kennedy, 2006, 2016). As teachers plan, implement, and revise their practices over time, they consider multiple interactions between the content they are covering, the learning processes and experiences they intend to scaffold, the instructional methods they might use to support students’ participation, the lesson flow and momentum they want to achieve, the classroom community

norms they wish to instil, and their own personal needs (Kennedy, 2006). Understanding how and when critical thinking can be supported in science instruction is fundamentally a consideration of how critical thinking should play out within the practices of teachers who develop and implement such instruction.

Teachers' discussions about their instructional practices tend to be expressed in terms of *lines of thinking* that encompass past experience, beliefs, and values, as well as *intentions*—a complex combination of teachers' goals, avoidances, aspirations, perceived obligations, and personal needs (Kennedy, 2005). Efforts to identify and train teachers' core practices—the patterns of observable instructional behaviours that characterise their instructional approaches (Kennedy, 2016)—can fail without a clear understanding of the instructional intentions that underly their effective deployment by experienced teachers. Training or characterisations of core practices for instruction are prone to error unless they incorporate meaningful understanding of why teachers prioritise and implement specific practices as they navigate classroom challenges (Ghousseini, 2015; Kennedy, 2016). From this perspective, efforts to identify best practices in instructional behaviours are incomplete if they do not explore teachers' goals, values, and concerns as their foundation.

Kennedy's (2016) integrated approach to instructional practice identifies five persistent challenges that influence teachers' selection, sequencing, and deployment of classroom activities, in addition to influencing when and how teachers decide to intervene in the face of student difficulties: portraying the curriculum, enlisting student participation, exposing student thinking, containing student behaviour, and accommodating personal needs/preferences. These five challenges not only drive instructional practice, but they also combine to influence the ways in which teachers interpret what they see in their classrooms (Kennedy, 2016). When thinking about larger-scale domains of study in classrooms, these challenges can be conceptualised in terms of the domain, the student, and the teacher: domain-relevant processes and content (curriculum), learners' engagement (student participation), learners' cognitive processes and outcomes (student thinking), learners' noncognitive processes and outcomes (student behaviours), and teacher considerations (personal needs/preferences). Since teachers' personal needs and preferences (e.g. tolerance for classroom noise, level of organisation) are likely to remain relatively constant across varied domains, exploring domain-based instructional practices warrants clear attention about teachers' goals and avoidances aligned to domain- and student-focused challenges.

Critical-thinking in science: domain-focused challenges in instructional practice

While scientific reasoning inherently requires domain-specific conceptual knowledge as well as an understanding of scientific conventions, it also builds strongly upon a foundation of scientific reasoning that aligns to specific critical thinking skills; these include analysis, interpretation, inference, evaluation, and explanation (Dowd et al., 2018). Some researchers suggest that the alignment between critical thinking and scientific reasoning is so fundamental that educators should consider redefining critical thinking in science as teaching students 'how to think like a scientist,' using evidence-based approaches to evaluate claims and reject unsupported ideas (Schmaltz et al., 2017). From this perspective, critical thinking in science reflects the scientific thinking and

behaviours that align to activities of professional scientists. However, there is little evidence about how teachers themselves approach or observe student critical thinking in science.

From a domain-focused standpoint, much research on critical thinking in science has been focused on the design of strategic learning materials and tools (Bulgren & Ellis, 2015; Hussein et al., 2019; Ismail et al., 2018; Muntaha et al., 2021) or the evaluation of student work products (Lamb et al., 2021). Other research has examined the impact of pre-service teachers' domain-related prior experiences (Hancock & Gallard, 2004) on their implementation of inquiry-based, authentic science instruction. While there is value in these content- and experience-based approaches, moving towards an understanding of the ways in which teachers approach, conceptualise, and evaluate critical thinking during science lessons is central to understanding how they may select and implement instructional strategies to support effective critical thinking in science.

Critical thinking in science: student-focused challenges in instructional practice

During classroom activities focused on critical thinking, students are likely to exhibit significant struggle since critical thinking is difficult to master and requires repeated practice opportunities (van Gelder, 2005). Even for instructors, willingness to engage in effortful thinking is predictive of enhanced critical thinking performance (Janssen et al., 2019). For teachers, the potential for student struggle and confusion may be viewed negatively—as potential avoidances—in light of the student-focused classroom challenges they face. Teachers may consider student struggle and confusion as factors that are likely to reduce engagement (participation), frustrate learners (resulting in problematic behaviours), or introduce errors or misconceptions (student thinking).

In their attempts to mitigate these student-related challenges, teachers' approaches to (or evaluations of) critical thinking during science learning may not align to approaches espoused by researchers in learning science and science education. Learning researchers repeatedly have found that students can benefit from confusion (D'Mello et al., 2014; Lodge et al., 2018), failure (Kapur & Rummel, 2012; Kapur, 2008), and struggle (Fries et al., 2021), to the extent that some researchers have introduced purposeful errors into instructional materials to enhance student learning outcomes (Lehman et al., 2012; Richey et al., 2019). Principles for effective instructional design focused on in-depth learning emphasise not only creating opportunities for productive struggle through generative student activities, but the intentional design of instructional experiences that engage students in repeated struggle over time (Fries et al., 2021). From the perspective of research in learning, confusion, struggle and uncertainty are inherent to deep student learning.

Researchers in science education also have emphasised the productive nature of uncertainty (Chen et al., 2019). However, research in science instruction has identified that teachers often are uncomfortable with student uncertainty; science teachers in particular may view uncertainty negatively and focus, instead, on established knowledge in the domain (Donnelly, 1999). Even when teaching inquiry-based lessons, science teachers may prematurely reduce student uncertainty by emphasising data as a way to find answers and prove ideas (Chen et al., 2019; McNeill & Berland, 2017). While inquiry-based investigations can provide rich opportunities for students to learn about

a topic via self-directed investigations with teacher guidance (Lazonder & Harmsen, 2016), productive learning and discussion during science inquiry is enhanced when teachers do not simply acknowledge and resolve uncertainty, but rather maintain it to support deep reasoning and sustained engagement with data patterns and competing ideas (Chen & Techawitthayachinda, 2021; Chen et al., 2019). These findings are consistent with reform-based approaches to science learning reflected in the Next Generation Science Standards (NGSS, 2014), which emphasise the importance of generative, inquiry-based activities in establishing science as a process (with inherent uncertainties) rather than settled knowledge.

Enacting ambitious (inquiry-based) instruction consistent with NGSS approaches puts significant demands on teachers to create repeated, in-depth opportunities for students to revisit, reshape and deepen their understanding of difficult concepts (Stroupe, 2015). Facilitating comfort with uncertainty and struggle can create even greater demands that may not be well-aligned to teachers' conceptions of persistent challenges in their classrooms (Kennedy, 2016). Even if teachers recognise the curriculum relevance and value of critical thinking during science, they may be reluctant to enact these practices if they sense that it will frustrate students or reduce participation and engagement, creating opportunities for off-task behaviours or boredom.

Research with pre-service teachers has explored perceived alignment between science standards and critical thinking processes, showing that pre-service teachers routinely associate critical thinking with generalised scientific processes (e.g. explaining evidence, designing and conducting experiments) but have more difficulty thinking about critical thinking in relation to standards focused on domain concepts (Forawi, 2016). However, less is known about how practicing teachers conceptualise and value critical thinking as part of their science instruction in classrooms. In order to develop effective approaches to critical thinking in inquiry-based science instruction, it first is essential to understand how practicing science teachers conceptualise and evaluate critical thinking processes as aligned to their instructional practices and student outcomes.

Materials and methods

Research Quest: inquiry-based science investigations for critical thinking

Middle school science teachers' implementation of a Research Quest investigation in palaeontology (www.researchquest.org) served as the basis for exploring their perceptions, observations, and evaluations of student critical thinking processes. Research Quest investigations leverage digitised materials from natural history museum collections to support authentic student research on a scientific question, with a focus on scaffolding students' critical thinking processes and outcomes (Butcher et al., 2017, 2019, 2021). Investigations are designed to support authentic, inquiry-based research activities in middle school science classrooms—students work collaboratively to ask questions, make observations, document their evidence, analyse findings, evaluate ideas, develop arguments, and communicate conclusions (Butcher et al., 2017). Investigations are designed to be student-centred and open-ended, with the goal of helping students move from simple forms of critical thinking (e.g. finding and selecting evidence) to more complex processing (e.g. interpreting data patterns, developing evidence-based

arguments). Examining how teachers approach, identify, and evaluate students' critical thinking processes surrounding the implementation of a Research Quest investigation helps identify intentions (goals and avoidances) that focus and inform teacher practice.

Ethics committee review

The Institutional Review Board at the University of Utah determined that all phases of this project met the standard of 'quality improvement' activities and determined that this work did not meet the definitions of Human Subject Research according to Federal regulations (45 CFR 46.102(d)).

Teacher data was gathered during classroom implementation and revision cycles that informed Research Quest development. Analyses were organised into three phases aligned to the research questions. Phase 1 examined teachers' existing approaches to critical thinking in science, examining their ideas and values *before* implementing the online science investigation (RQ 1). Phase 2 examined teachers' observations and evaluations of critical thinking *after* implementing the target science investigation, using data from a small sample of teachers without specialised training in science instruction (RQ 2). Phase 3 provided a more in-depth exploration of teachers' observations and evaluations of students' critical thinking processes *after* the implementation of the online science investigation, this time exploring perspectives of a small sample of teachers with specialised training in science instruction (RQ 2).

Phase 1: teacher perceptions and approaches to critical thinking in science

Phase 1 examined the critical thinking approaches of a sample of science teachers who expressed an interest in implementing the Research Quest investigation in their classes but had not yet done so.

Participants

Participants were recruited via an email solicitation to regional middle schools seeking teachers who wished to implement an online, inquiry-based investigation designed to support critical thinking into their science instruction. Participants were 37 teachers who taught science in middle schools in the Western United States. Overall, participants reported an average of 11.4 years of classroom teaching. The majority of participants ($n = 21$) were highly experienced, having more than a decade of classroom experience ($M = 17.4$, $SD = 6.8$); nine participants were moderately experienced, having 5–9 years of classroom experience ($M = 6.7$, $SD = 1.3$); the remaining seven participants had lower levels (less than 5 years) of classroom experience ($M = 2.4$, $SD = 1.5$). Teachers varied in the extent to which they had received specialised training in science instruction. Overall, 19 teachers had at least a single endorsement in science teaching (subsample $M = 2.06$, $SD = 0.77$), with 14 teachers having 2 or more science endorsements.

Responding teachers taught at 34 different schools. Fourteen schools had low rates (less than 20%) of low-income enrolment ($M = 13.8\%$; range = 4.9% – 18.4%); 11 schools had moderate rates (20–49%) of low-income enrolment ($M = 33.1\%$; range = 20.5% – 45.5%), and 12 schools had high rates (50% or higher) of low-income enrolment ($M = 65.2\%$; range = 51.3% – 91.2%). Rates of enrolment by racial-ethnic minorities or

multiple-race students was low (less than 20%) for 19 schools ($M = 14.0\%$; range = 3.8% – 19.7%), moderate (20–49%) for 13 schools ($M = 31.8\%$; range = 23.4% – 45.9%), and high (50% or higher) at five schools ($M = 64.5\%$; range = 58.3% – 80.3%).

Phase 1 materials and procedure

Participants completed an online survey before they implemented the inquiry-based investigation with students. The survey asked teachers to provide demographic information (e.g. years of teaching experience, district, school) as well as to complete 10 Likert-style items that assessed perceptions of effective critical thinking in inquiry-based science instruction. As seen below, five items (Q1 – Q5) assessed teacher perspectives on critical thinking processes proposed to be inherent in scientific reasoning, including analysis, reflection, collaboration, and critique (Dowd et al., 2018; Schmaltz et al., 2017). These items were consistent with generative, student-centred approaches to science learning aligned to NGSS (NGSS, 2014) and reflected positive goal intentions (Kennedy, 2016) relevant to content- and student-focused challenges for inquiry-based science classrooms.

Five items (Q6 – Q10, *in italics below*) assessed teachers' avoidance intentions related to student-focused challenges in critical thinking: preventing confusion and uncertainty, reducing opportunities for struggle, and shortening inquiry cycles. Agreement with these items reflects a divergence from research-based recommendations to embrace confusion (D'Mello et al., 2014), maintain uncertainty (Chen & Techawitthayachinda, 2021), and engage students in repeated opportunities to struggle with challenging content (Fries et al., 2021; Stroupe, 2015).

For all 10 Likert-style items, teachers were presented with the following prompt and items and asked to rate each one on a (labelled) 6-point scale (1 = Strongly Disagree, 2 = Disagree, 3 = Slightly Disagree, 4 = Slightly Agree, 5 = Agree, 6 = Strongly Agree):

Prompt: In my opinion, effective inquiry activities should:

Q1: Use authentic materials and questions for student work and research.

Q2: Give students ample opportunities to reflect on what they've learned.

Q3: Give students freedom to identify their own questions and approaches.

Q4: Encourage collaboration among learners without direct guidance from teachers.

Q5: Make students' ideas available for critique by other students.

Q6. *Provide step-by-step instructions so that students don't feel confused.*

Q7. *Provide students with clear questions that allow them to determine the ultimate success or failure of their approach.*

Q8. *Include close teacher supervision to ensure students don't veer off-track.*

Q9. *Include frequent checks of understanding, to keep students moving forward without struggling.*

Q10. *Limit collaboration periods to be short and focused, keeping students focused on a single question or task.*

Teachers' agreement ratings were coded and analysed for patterns of agreement on the goal intention items (Q1 – Q5) and avoidance intention items (Q6 – Q10). In addition, a composite score (Effortful Critical Thinking in Inquiry) was created using aggregate teacher responses; this composite score reflected the extent to which teachers' pre-implementation approaches aligned to research-based characterisations of critical thinking processes and an embrace of student struggle and uncertainty. Q1 – Q5 received standard scoring aligned with participant ratings (e.g. teacher rating of 1: Strongly Disagree = score of 1) and Q6 – Q10 were reverse scored (e.g. teacher rating of 1: Strongly Disagree = score of 6). Higher scores reflect both teacher agreement with inquiry-based goal intentions and disagreement with avoidance intentions that reduce struggle or uncertainty. Lower scores can reflect disagreement with research-based approaches to critical thinking in science, agreement with avoidance intentions to reduce struggle/uncertainty, or both. Maximum score was 60 (6 points X 10 items).

Results

As seen in Table 1, teachers at all levels of classroom experience (low, moderate, and high) exhibited relatively strong agreement with goal intention items related to science inquiry and critical thinking (Q1 – Q5). Teachers also exhibited mild to moderate agreement with the avoidance intention items (Q6 – Q10). Overall patterns of agreement with goal and avoidance intention items generally were consistent across all levels of teaching experience, except that teachers with moderate levels of experience (5–9 years of classroom teaching) dipped into mild disagreement for two avoidance items (Q6 and Q8).

Because specialised training in science instruction may influence teachers' comfort and agreement with research- and reform-based approaches to science learning, teacher responses also were analysed for those who held at least one endorsement in science teaching ($n = 19$) and those who had not earned a science teaching endorsement ($n = 18$).

Table 1. Means (and standard deviations) of item agreement, grouped by level of classroom teaching experience, training in science instruction, and critical thinking in inquiry scores. Scores reflecting disagreement are presented in bold.

	Goal Intentions: Generative Scientific Reasoning					Avoidance Intentions: Prevent Student Struggle, Confusion				
	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10
Classroom Teaching Experience										
Low	5.4	5.6	5.5	5.8	4.6	4.4	4.4	4.8	5.1	5.1
($n = 7$)	(.74)	(.74)	(.76)	(.46)	(1.1)	(1.4)	(1.4)	(1.2)	(.99)	(.99)
Moderate	5.4	5.0	5.0	5.4	4.0	3.6	4.3	3.6	5.0	5.0
($n = 9$)	(.79)	(1.0)	(1.0)	(.79)	(1.2)	(2.0)	(1.6)	(1.4)	(1.2)	(1.2)
High	5.6	5.7	5.6	5.5	5.2	4.0	4.7	4.4	5.0	5.0
($n = 21$)	(.58)	(.55)	(.49)	(.67)	(.81)	(1.6)	(1.4)	(1.3)	(1.1)	(1.1)
Specialised Science Training										
No	5.6	5.6	5.4	5.56	4.8	4.3	4.5	4.4	4.9	4.9
($n = 18$)	(.70)	(.78)	(.78)	(.70)	(1.0)	(1.6)	(1.6)	(1.2)	(1.4)	(1.4)
Yes	5.5	5.6	5.6	5.5	4.9	3.8	4.6	4.3	5.2	5.2
($n = 19$)	(0.6)	(0.7)	(0.6)	(0.6)	(1.1)	(1.6)	(1.2)	(1.4)	(0.7)	(0.7)
Score: Effortful Critical Thinking in Inquiry										
Lower	5.5	5.5	5.4	5.5	4.8	5.3	5.3	5.2	5.6	5.6
($n = 19$)	(.77)	(.84)	(.84)	(.70)	(1.2)	(.93)	(1.1)	(.98)	(.68)	(.68)
Higher	5.6	5.7	5.6	5.5	4.9	2.7	3.9	3.4	4.4	4.4
($n = 18$)	(.50)	(.60)	(.51)	(.62)	(.90)	(1.0)	(1.4)	(.92)	(1.1)	(1.1)

Table 2. Major themes drawn from qualitative teacher feedback during pilot implementation of a student-centred, inquiry-based investigation for critical thinking.

Valence	Observations	% Teachers	Sample Quote(s)
Positive	Students benefitted from finding, selecting, and analysing evidence.	75%	'The most beneficial activity was finding evidence to back up their claims.' '[Students developed] the ability to look for and analyse the data.'
	Students considered multiple sources and developed new insights.	50%	'Having a gradual build of access to knowledge helped them consider all possibilities and not feel overwhelmed.'
	Students engaged in peer discussion & critique.	50%	'[Most valuable part was] being able to share ideas with others in their groups.'
Negative	Students expressed confusion, disagreement, and/or uncertainty.	50%	'My students could have used a little more direction ... They weren't always sure what would be good evidence and what wouldn't.'
	Students struggled to manage time and to finish tasks quickly.	37.5%	'Give a time frame for discussion. Then, give a time frame for documentation.' 'Give 1 step of instructions—short discovery then move on quickly to next instruction.'
	Students did not make continuous progress, made errors, and (at times) pursued ineffective approaches.	37.5%	'They could figure it out on their own but would have had a more solid understanding if they had been prompted to self-assess more.'

As seen in [Table 1](#), patterns across these two groups of teachers were largely similar, expect that teachers with a science endorsement mildly disagreed with a single avoidance intention item: Q6. *Provide step-by-step instructions so that students don't feel confused.*

To explore patterns in the approaches to critical thinking between teachers with differing pre-implementation approaches, a median split was performed on composite scores of Effortful Critical Thinking in Inquiry (median score = 37). This split resulted in 19 teachers with lower overall scores and 18 teachers with higher overall scores. As seen in [Table 2](#), both groups of teachers showed strong agreement with goal intention items related to scientific reasoning and student-centred inquiry. Thus, differences in the composite scores cannot be attributed to differences in teachers' goal intentions. However, across the groups, there were varied patterns of agreement with avoidance intention items. Teachers with higher composite scores prior to implementation showed mild to moderate disagreement with three items addressing the use of teacher scaffolding and monitoring to prevent confusion or nonlinear processes (Q6, Q7, Q8).

Phase 1 discussion

Results from phase 1 suggest that, at least for science teachers who seek to implement an inquiry-based investigation for critical thinking in their classrooms, length of teaching experience does not predict the prevalence of goal or avoidance intentions. This finding is not entirely consistent with previous research showing that practicing teachers' beliefs about effective critical thinking processes tend to narrow over time (Torff, 2005). However, previous research used a larger, random sample of teachers not limited to science educators. The current sample—science educators interested in inquiry-based investigations for critical thinking—may have more robust goal intentions related to generative, student-centred learning. Current results may reflect that critical thinking

goal intentions might be more common among science teachers who embrace inquiry-based instruction than in overall populations of teachers across multiple subject matters.

However, even teachers with specialised training in science instruction expressed avoidance intentions as they prepared to engage their students in critical thinking during science inquiry. Teachers with one or more science endorsements were just as likely to agree with avoidance intentions related to preventing student struggle, reducing confusion, and resolving uncertainty as teachers without a science teaching endorsement. Thus, even trained science teachers are likely to agree with avoidance intentions that are in conflict with research-based recommendations to embrace student confusion and struggle (D'Mello et al., 2014; Lodge et al., 2018). These findings may reflect the importance of teacher attention to persistent classroom challenges focused on student participation, thinking, and behaviours (Kennedy, 2016), suggesting a disconnect between the practices that are prescribed for teachers vs. those selected and deployed by practicing teachers as they seek to support critical thinking in science.

Examining item agreement for teachers with higher vs. lower composite scores on Effortful Critical Thinking in Inquiry highlights an interesting pattern. Teachers with lower or higher scores were not distinguished by their agreement with goal intentions related to science practice and student processes (e.g. analysis, inference, argument). Teachers reliably agreed that these observable processes were valuable aspects of critical thinking, consistent with previous arguments about strong overlap between scientific thinking and critical thinking (Schmaltz et al., 2017). Thus, differences in composite scores were not attributable to differences in teachers' relevant goal intentions. Results show that differences were tied to varied agreement on items that targeted avoidance intentions related to student struggle. Teachers with lower composite scores showed moderate to strong agreement with avoidance intentions—i.e. instructional strategies to prevent confusion, remove struggle, and reduce uncertainty. This pattern underscores the need to attend to avoidance intentions (Kennedy, 2016) in order to fully understand teachers' instructional practices surrounding critical thinking in science.

However, phase 1 explored teachers' existing approaches *before* the implementation of an online, inquiry-based investigation for critical thinking in their classrooms. Research Quest investigations are scaffolded, online learning experiences that support teachers and learners with student-paced learning progressions, just-in-time guidance, scaffolded instruction, strategic prompts/questions to focus student thinking, and supports for documenting and analysing patterns of evidence. This type of online investigation off-loads some teacher demands (e.g. planning, pacing, materials selection, prompt delivery) to the online environment, allowing teachers to more easily 'float' the classroom during investigations and provide in-depth student support and interactions. Thus, it is possible that teachers' observations and evaluations of critical thinking during these scaffolded, online investigations will reflect a different pattern of goal and avoidance intentions than those expressed by teachers prior to implementation.

Phase 2: teachers' observations and evaluations of students' critical thinking

Phase 2 examined observations and evaluations of students' critical thinking from a small sample of teachers after they completed the Research Quest palaeontology investigation in their classrooms.

Participants

Participants were eight 6th grade science teachers from schools in the Western United States. Participating teachers were recruited via an email invitation to regional 6th grade teachers to implement an inquiry-based science investigation for critical thinking into their classrooms during a targeted two-week window, with efforts to include a balance of teachers from urban Title I schools and rural schools. Demographic information was not provided by one teacher. Of the remaining sample, three teachers had been teaching for less than 5 years ($M = 2.3$, $SD = 1.5$); two teachers had been teaching for 5–9 years ($M = 6.5$, $SD = 0.7$), and two teachers had been teaching for more than a decade ($M = 19.5$, $SD = 3.5$). No teacher had earned an endorsement in science teaching.

Four teachers taught at separate Title I urban schools; three urban schools had high enrolment (50% or higher) of low-income students (55.0%; 67.0%; 89.2%) and one school had moderate enrolment (20–49%) of low-income students (41.2%). The four urban schools ranged from high to moderate representation of racial-ethnic minorities and multiple-race students (School 1: 77.5%; School 2: 47.0%; School 3: 26.3%; School 4: 21.8%). The remaining four teachers taught at two rural schools in the same state as the urban schools (two teachers per school); one rural school had moderate enrolment by low-income learners (47.6%) and one rural school had high low-income enrolment (65.9%); both rural schools had moderate enrolment by racial-ethnic minorities and multiple-race students (School 5: 22.1%; School 6: 27.5%).

Phase 2 materials and procedure

Research Quest investigations represented approximately 5–6 hours of student activity, separated into two sessions encompassing different stages of the investigation: data gathering and synthesis/communication. Sessions were completed either on the same day or on consecutive instructional days. The online investigations guided students to investigate two key questions that would be asked by a palaeontologist after uncovering a new fossil: (1) What bone has been found? (2) To what dinosaur does it belong? Across the investigation, students used 3D fossil prints, printed (paper) fossil maps/guides, curated online resources, and 3D scans of fossils on a tablet device to make observations, generate inferences, and develop evidence-based arguments. During the investigation, students iteratively engaged in collaborative discussion and completed a ‘research notebook’ where they documented their evidence, ideas, and arguments. The instructional flow of learning activities was guided via the online investigation.

Within one day of completing the investigation, teachers completed an online feedback form about their classroom observations and experiences in using the investigation. To explore teachers’ thinking on student’s critical thinking processes, three free-form items asked teachers to describe observations of the ‘most valuable’ aspects of the investigation for student learning, ‘least valuable’ aspects of the investigation for student learning, and suggested ‘changes or improvements’ in the investigation to support critical thinking. Teachers’ free-text responses on these three items were extracted and segmented into idea units (Trickett & Trafton, 2007) and coded via thematic analysis (MacQueen & Namey, 2012). Major themes were identified as those represented in 35% or more of the teacher sample (i.e. identified by at least 3 teachers). After major themes had been identified, they were organised by valence: positive valence (aspects of the investigation and critical thinking that teachers valued) and negative (aspects of the investigation and

critical thinking that teachers did not value or reported as needing revision before future implementation).

Results

As seen in Table 2, six major themes relevant to students' critical thinking processes were identified. Three themes had positive valence—these themes reflected positive teacher evaluations of how their students engaged in critical thinking processes during inquiry-based science learning. Teachers particularly valued the ways that they observed students gathering evidence (i.e. finding, selecting, and analysing data), evaluating evidence (i.e. considering multiple sources and developing new insights), and communicating ideas (i.e. peer discussion and critique). However, several teachers (37.5–50% of the sample) observed student processes during critical thinking that they considered to be problematic. Negative themes focused on student confusion, disagreement, or uncertainty (mentioned by 50% of the sample), struggles with time management and efficiency (mentioned by 37.5% of the sample), and lack of continuous, error-free progress during an investigation (mentioned by 37.5% of the sample).

Phase 2 discussion

The critical thinking processes that teachers observed and valued *following* an inquiry-based investigation were largely consistent with the goal intentions expressed by teachers *before* implementation in phase 1. Overall, positive observations tended to reflect critical thinking processes (e.g. gathering data, evaluating evidence) that researchers have proposed to be inherent in science (Dowd et al., 2018; Schmaltz et al., 2017). Taken together, teachers' observations and evaluations reflected the central importance of curriculum- and student-focused goal intentions in informing teachers' instructional practice (Kennedy, 2016), even when implementing a scaffolded, online investigation for critical thinking with substantial embedded supports.

However, teachers in this sample expressed discomfort with some of the effortful aspects of critical thinking exhibited by students during an inquiry-based investigation. Although critical thinking is a difficult skill in which students are likely to struggle across repeated practice (van Gelder, 2005) and the research literature emphasises potential benefits of facilitating student confusion (D'Mello et al., 2014), teachers who observed students engaged in these processes were likely to suggest instructional revisions focused on adding teacher direction to make critical thinking tasks shorter and more tractable for students. That is, although teachers in this sample observed instances of student uncertainty during critical thinking in inquiry, they did not recognise uncertainty as productive or 'adapt it as a resource' (Chen et al., 2019, p. 1237). Teachers were likely to endorse multiple avoidance intentions for future implementation, potentially as a means to avoid reduced student participation or frustration—persistent student-focused challenges that must be addressed by teachers as they plan instruction (Kennedy, 2016). Given these findings, attempts to move teachers away from their expressed avoidance intentions related to students' critical thinking during science inquiry may have limited impact, as these approaches largely ignore the persistent student-focused challenges that teachers must balance and address in their practice (Kennedy, 2005, 2006). Informing instructional practice

related to critical thinking in science may require a more detailed understanding of how teachers' observations and evaluations inform goal (not avoidance) intentions related to target learning outcomes.

Phase 3: aligning critical thinking processes to observed outcomes

Phase 3 examined science teachers' observations and evaluation of students' critical thinking processes and learning outcomes following an inquiry-based science investigation, using a small sample of teachers with specialised training in science instruction. This phase focused on critical thinking processes and learning outcomes aligned to teachers' goal intentions for inquiry-based investigations.

Participants

Participants were ten practicing science teachers from seven middle schools in the Western United States who completed the Research Quest investigation on palaeontology in their classes following an email invitation to implement the investigation during a targeted two-week window. Two teachers had one year of classroom experience; the remainder of the sample had a decade or more of teaching experience ($M = 15.2$, $SD = 11.4$). All teachers in the sample had earned multiple endorsements in science instruction ($M = 3.0$, $SD = 1.1$). Enrolment by low-income students varied across the seven schools: three had high enrolment (51.4%; 62.6%; 82.8%), three had moderate enrolment (22.5%; 38.7%; 41.1%), and one had low enrolment (14.5%). Schools also varied in the enrolment by racial-ethnic minorities and multiple-race students: two had high enrolment (56.4%; 76.3%), three had moderate enrolment (26.8%; 29.2%; 39.9%), and two had low enrolment (8.5%; 15.8%).

Phase 3 materials and procedure

Within one day of their class completing the Research Quest investigation on palaeontology (implemented as in phase 2), participating teachers completed the implementation survey online. In addition to providing general feedback on the investigation (e.g. alignment to standards, appropriate length), teachers responded to eight Likert-style items designed to assess their observations of students' critical thinking processes and outcomes, using the same labelled scale as the Likert-style items in phase 1. Teachers responded to all eight items twice—once for observations related to the data gathering stage of the investigation and once for observations related to the synthesis/communication stage of the investigation. Two items asked teachers to rate the extent to which they had observed two potential student *outcomes*: 'critical thinking skills' and 'communication and collaboration skills.' The remaining six items queried teachers about the extent to which they had observed students engage in six *critical thinking processes* during the investigation: making high-quality observations, tracking observations and evidence, evaluating the strength and quality of evidence, creating strong arguments, evaluating the strength and quality of arguments, and considering multiple perspectives. Teacher ratings of observed outcomes and critical thinking processes were correlated using Spearman's rho (a non-parametric test appropriate for ordinal data).

Table 3. Correlations (Spearman's rho) between teacher ratings of observed outcomes and critical thinking processes during the data gathering and synthesis/communication stages of an inquiry-based investigation.

	CT	CC	OBS	EVID	EVAL-EV	ARG	EVAL-ARG	MULT
Data Gathering								
CT	—							
CC	.33	—						
OBS	.67*	.00	—					
EVID	.51	.22	.76*	—				
EVAL-EV	1.0**	.33	.67*	.51	—			
ARG	.58	.62	.63	.71*	.58	—		
EVAL-ARG	.60	.80**	.25	.44	.86**	.60	—	
MULT	.67*	.00	1.0**	.76*	.63	.67*	.49	—
Synthesis/Communication								
CT	—							
CC	.83**	—						
OBS	.52	.44	—					
EVID	.52	.44	1.0**	—				
EVAL-EV	.51	.60	.51	.51	—			
ARG	.41	.67*	.69*	.69*	.61	—		
EVAL-ARG	.43	.68*	.44	.44	1.0**	.60	—	
MULT	.05	.04	.52	.52	.69*	.51	.44	—

Outcomes: *Critical Thinking (CT)*; *Communication/Collaboration (CC)*. Student processes: Making High-Quality Observations (OBS); Tracking Observations & Evidence (EVID); Evaluating Strength & Quality of Evidence (EVAL-EV); Creating Strong Arguments (ARG); Evaluating Strength & Quality of Arguments (EVAL-ARG); Considering Multiple Perspectives/Possibilities (MULT).

Results

As seen in Table 3, observed critical thinking process were associated with observed student outcomes, but the nature of these associations varied depending upon the stage of the investigation being completed by students (data gathering vs. synthesis/communication). During data gathering, critical thinking outcomes were significantly, positively correlated to making high-quality observations (OBS), evaluating the strength and quality of evidence (EVAL-EV), and considering multiple perspectives/possibilities (MULT). Teachers who more frequently observed students engaged in these processes were more likely to observe student learning outcomes related to critical thinking. During this initial stage of the investigation, communication/collaboration outcomes (CC) were significantly correlated only with students evaluating the strength and quality of arguments (EVAL-ARG) as they worked with the evidence they gathered.

During the subsequent stage of the investigation—synthesis/communication—the frequency with which teachers observed students engaging in targeted critical thinking processes was no longer correlated with students' observed critical thinking outcomes. During this later stage of the investigation, only communication/collaboration outcomes were correlated with the observed frequencies of students' critical thinking processes. Communication and collaboration outcomes were significantly, positively correlated to the frequency with which teachers observed students creating strong arguments (ARG) and evaluating the strength and quality of arguments (EVAL-ARG). By the end of the investigation, science teachers saw outcomes as highly related: there was a strong, positive correlation

between observed critical thinking outcomes and observed communication/collaboration outcomes in the final, synthesis/communication stage.

Phase 3 discussion

Correlations between teachers' observations of student critical thinking processes and varied learning outcomes suggest that the structure of science investigations likely plays a role in the distribution of students' processes, with resulting implications for how teachers may set goal intentions for critical thinking in science inquiry. During the initial, data-gathering stage of the investigation, teacher ratings suggest that students' critical thinking processes related to evidence (i.e. making high-quality observations, evaluating strength and quality of evidence, and considering multiple perspectives/possibilities) are strongly aligned to observed (initial) critical thinking outcomes. These alignments suggest that teachers may, at least initially, prioritise goal intentions that emphasise critical thinking as a process of gathering and evaluating evidence during inquiry-based learning. Teachers may not emphasise more procedural activities (i.e. tracking evidence) or reflective activities (i.e. creating or evaluating arguments) at this stage.

As students move away from data collection and analysis towards communication and critique, the critical thinking processes that teachers readily observe and value shift towards those focused on explanations and arguments (i.e. creating and evaluating arguments). Teachers perceive these argument-based aspects of critical thinking as central to communication outcomes; they also perceive communication outcomes at the end of an investigation as strongly, positively correlated to final critical thinking outcomes. This suggests that teachers may see critical thinking outcomes as strongly aligned to students' component cognitive processes early in an investigation but as a more holistic (communication-centred) outcome by the end of an investigation.

Taken together, these data suggest that the goal intentions of science teachers' implementing inquiry-based investigations for critical thinking are sensitive to the changing nature of student work across the investigation. These data also suggest that a more nuanced approach to supporting critical thinking during science learning may be warranted, with target strategies evolving across an investigation and acknowledging that the focus of teacher observations may change their priorities across the course of an investigation.

General discussion

Overall, this work suggests a potential disconnect between research-based recommendations for student critical thinking during inquiry-based science investigations and the range of intentions set by teachers who must balance conflicting classroom challenges. Findings also suggest strong alignment between RQ 1 and RQ 2—science teachers' approaches to critical thinking *before* implementation of an inquiry-based investigation were strongly aligned the perspectives of their peers *after* completing the inquiry-based investigation. Before (phase 1) and after (phase 2) implementation of an inquiry-based investigation, teachers strongly endorsed student critical thinking processes that corresponded to alignments between critical thinking and science inquiry proposed in the research literature (Dowd et al., 2018; Schmaltz et al., 2017). From an integrated perspective on instructional practice (Kennedy, 2005, 2016), teachers set goal intentions that were balanced across inherent characteristics of the domain (i.e. portraying the

curriculum) and desired cognitive processes of students (i.e. exposing *successful* student thinking).

However, teachers also readily expressed avoidance intentions that are inconsistent with research-derived perspectives that student confusion and struggle during a learning opportunity support enhanced outcomes (D'Mello et al., 2014; Lodge et al., 2018), that students should be given repeated opportunities to struggle (Fries et al., 2021), and that science inquiry, in particular, benefits from teacher practices that serve to maintain uncertainty across an investigation (Chen & Techawitthayachinda, 2021; Chen et al., 2019). Avoidance intentions were not clearly related to teachers' experience or training—patterns of agreement with avoidance intentions were largely consistent regardless of classroom experience and across groups of teachers who did and did not have specialised training in science instruction (phase 1). Findings demonstrated that similar avoidance intentions were expressed both before (phase 1) and after (phase 2) the implementation of an inquiry-based investigation that was designed to support critical thinking and that provided multiple instructional scaffolds and embedded materials. As such, the avoidance intentions identified in this research do not appear to be strongly tied the demands that teachers would face in creating, planning, or implementing instructional moves or materials. So, what might be driving these avoidance intentions?

In this research, avoidance intentions that were evident in teachers' approaches and observations were strongly focused on reducing or preventing student errors, struggle, confusion, and uncertainty. These processes connect to persistent, student-focused challenges in the classroom: student thinking, student participation, and student behaviours (Kennedy, 2016). There are clear potential links across these student-focused challenges; for example, a student may not be able to resolve their confusion and uncertainty (student thinking), leading them to disengage (student participation), and potentially act out as they experience resulting negative emotions (student behaviour). Avoidance intentions related to these concerns likely reflect the reality that teachers must consider the far-reaching effects that difficulties in cognition can have on students' classroom experiences. Efforts to improve instructional practices for critical thinking in science may be misguided if they seek to change avoidance intentions related to student struggle without fully understanding how students' cognitive struggles can broadly influence emotional outcomes and classroom engagement. Informing and supporting effective instructional practices for critical thinking may require more nuanced, fine-grained assessment of students' processes and outcomes in ways that can be aligned to teachers' goal intentions.

Indeed, instructional guidance for critical thinking in science may need to reflect the ways that students' processes align to outcomes at different stages of an inquiry-based investigation. Phase 3 results demonstrated positive correlations between critical thinking processes that operate on pieces and patterns of evidence (i.e. making observations, evaluating evidence, and considering multiple possibilities) and observed critical thinking outcomes during the data gathering stage of an investigation. This suggests that (observable) component processes of cognition are related to perceived critical thinking outcomes at early stages of an investigation. Later in the investigation—when students were focused on synthesising and communicating arguments—critical thinking outcomes were not found to be tied to specific, component processes of critical thinking. Rather, late in the investigation, communication and collaboration outcomes (supported

by critical thinking processes focused on developing and evaluating arguments) were strongly, positively correlated to observed critical thinking outcomes. These findings may reflect that the processes of critical thinking targeted by instructional guidance should adjust over the course of an investigation, moving from evidence-based to argument-based priorities. They also suggest that teachers are more likely to conceive of critical thinking in terms of component processes early in an investigation and in more holistic ways by the end of an investigation.

Overall, current data suggest that students readily engage in critical thinking processes that teachers can observe during classroom investigations, making these processes amenable to the explicit instruction and reflection needed to support student development (Abrami et al., 2015). This research also demonstrates that the links between authentic, active learning opportunities and critical thinking skills that have been observed at the undergraduate level (Styers et al., 2018) can be observed by teachers in middle school classrooms. But, this research has found that avoidance intentions are prevalent in the ways teachers think about and evaluate inquiry-based investigations for critical thinking. Given this finding, one may question whether recommendations drawn from research-based ideals about student cognition (i.e. productive confusion and uncertainty) are unattainable or impede practice (Kennedy, 2005). However, current findings do not warrant such a broad or sweeping conclusion. Results do suggest that the realities of classroom teaching may lead science teachers to adopt avoidance intentions related to student thinking and behaviours even as they fully embrace student-centred, inquiry-based instruction. Thus, it may be most useful to develop materials and guidance that help teachers observe, evaluate, and track the ways that component cognitive process of critical thinking (aligned to goal intentions) should progress across the course of an investigation.

Limitations and future directions

The current work explored small samples of science teachers who chose to implement inquiry-based investigations for critical thinking into their classroom instruction. While this provides insight into the approaches and perspectives of practicing teachers who already have an interest in critical thinking for science education, it does not capture the perspectives or observations of teachers with limited (or negative) interest in integrating critical thinking into science instruction. Current work is not intended to examine population-level characteristics or to identify causal mechanisms or associated pathways that lead to the development of critical thinking knowledge in broad populations of teachers.

The current work examined teachers' perspectives before and after the implementation of an investigation centred on a single domain (palaeontology). Future work should examine teachers' observations, approaches, and evaluations of students' critical thinking processes across a range of activities on varied science topics. In addition, data collection focused strongly on two forms of teacher intentions—goals and avoidances—and did not address other aspects of teachers' intentions, including aspirations, obligations, or personal needs (Kennedy, 2005). As researchers continue to explore instructional practices surrounding critical thinking in science inquiry, it will be helpful to broaden our exploration of the full set of intentions that may influence teachers' approaches and actions in the classroom.

Conclusions

Practicing science teachers readily observe and value critical thinking processes aligned to scientific reasoning, suggesting that practicing science teachers are poised to adopt and utilise investigations centred on goal intentions related to domain content and exposing (successful) student thinking. However, practicing science teachers also express avoidance intentions related to student struggle and uncertainty and these avoidances are seen across teachers with varying levels of experience and training. As such, efforts to promote effective instruction for critical thinking during science inquiry may be best focused not on ‘correcting’ avoidance intentions but rather on helping science teachers identify and track component processes of students’ critical thinking as they unfold and progress across the course of an investigation.

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Notes on contributors

Kirsten R. Butcher is an Associate Professor in Educational Psychology at the University of Utah. Her research examines the impact of interactive technologies and multimedia materials on cognitive processes and learning outcomes. Recent work focuses on the design and assessment of online science investigations to support critical thinking in middle school classrooms.

Michelle A. Hudson is a PhD student in Learning and Cognition in the Department of Educational Psychology at the University of Utah. Her work explores the impact of tangible (e.g., 3D prints) and virtual (e.g., 3D models) materials on science learning, with particular focus on how and when 3D visualisations can facilitate in-depth reasoning and high-level cognition.

McKenna Lane is a Digital Learning and Curriculum Specialist at the Natural History Museum of Utah and a Ph.D. student in Curriculum and Instruction at the University of Illinois, Urbana-Champaign. Her work examines instructional supports for science learning in flexible contexts, with particular focus on activities and scaffolds for thinking critically about evidence.

Madlyn Larson is Associate Director of Education Initiatives at the Natural History Museum of Utah. Her work focuses on the development of technology-enabled learning experiences and supporting teacher materials to enhance K-12 students’ critical thinking skills. Ms. Larson leads development of the Natural History Museum of Utah’s premier, digitally-delivered programme: Research Quest.

ORCID

Kirsten R. Butcher  <http://orcid.org/0000-0002-7433-0972>

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