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Hannah Sevian [a]; Lisa Gonsalves [a]
[a] University of Massachusetts, Boston, MA, USA

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RESEARCH REPORT

Analysing how Scientists Explain their Research: A rubric for measuring the effectiveness of scientific explanations

Hannah Sevian* and Lisa Gonsalves
University of Massachusetts, Boston, MA, USA

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The present article presents a rubric we developed for assessing the quality of scientific explanations by science graduate students. The rubric was developed from a qualitative analysis of science graduate students' abilities to explain their own research to an audience of non-scientists. Our intention is that use of the rubric to characterise explanations of science by scientists, some of whom become professors, would lead to better teaching of science at the university level. This would, in turn, improve retention of qualified and diverse scientists, some of whom may elect to become science teachers. Our rubric is useful as an instrument to help evaluate scientific explanations because it distinguishes between the content knowledge and pedagogical knowledge of scientists, as well as a scientist's ability to integrate the two in the service of a clear and coherent explanation of his or her research. It is also generally useful in evaluating, or self-evaluating, science explanations by science professors and researchers, graduate students preparing to be scientists, science teachers and pre-service teachers, as well as students who are explaining science as part of learning.

Introduction

Scientific research is critical to the future of our world. The most important problems science currently faces are global, such as population growth, shrinking sources of biodiversity, and disease (American Association for the Advancement of Science, 1990). Yet, efforts to communicate the nature and results of scientific research are hindered by lack of training and emphasis on scientific communication to a general audience. Federal agencies have begun to place increased emphasis on scientists ensuring 'broader impacts' of their research. A significant first step toward having broader impacts is understanding how to explain science effectively to a general audience. We can look to the practices of exemplary science teachers

*Corresponding author. Graduate College of Education, University of Massachusetts, Boston, MA 02125, USA. Email: hannah.sevian@umb.edu

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for this understanding. Research shows that teachers with strong knowledge of their disciplines, and strong pedagogical practices, are more capable of using curriculum materials effectively (Cohen, Raudenbush, & Ball, 2003). Also, science is taught more effectively when a science teacher has training as a scientist because explaining science well involves cognitive abilities that are similar to the elements of scientific inquiry (Chinn & Malhotra, 2002). While significant resources are dedicated to improving the content knowledge of teachers due to this, we argue that it is also important to recognise that the converse is true—scientists are more effective at explaining science if they have training in pedagogy.

If content knowledge was sufficient for explaining science, all instruction at the university level would be exemplary. In fact, there is clear evidence at the K12 (primary and secondary school) level to indicate that pedagogy is important; that is, content knowledge alone is not sufficient in teaching well (Darling-Hammond, Holtzman, Gatlin, & Vasquez-Heilig, 2005). Students who begin at university are the same students who graduated from K12 schools, so this finding is relevant also to first-year university level, and possibly beyond. Poor science teaching—in particular, traditional instructional methods—is the most common complaint (83%) cited by undergraduate students (Seymour & Hewitt, 1997). With continued low involvement of under-represented groups in science, technology, engineering, and mathematics careers (Campbell, Jolly, Hoey, & Perlman, 2002), it is significant that improved science teaching also leads to improved retention of science, technology, engineering, and mathematics students (Barreto, 2002). To improve science teaching, we must train those who teach science at the university level in effective explanation of science.

The National Science Foundation has taken a step in this direction with its Graduate-K12 (GK12) programme. This programme, currently in its fifth year, aims to give future scientists (science graduate students) year-long experiences in K12 classrooms. The overall goal of the programme is to encourage the scientists to develop a lifelong commitment to science teaching—not for them to become K12 science teachers, but for them to join the world of research scientists who maintain their commitment to K12 education. Several leaders of GK12 projects nationwide reported at a recent national meeting of the GK12 programme that graduate students have experienced an increased ability to communicate their own research more effectively. They attributed this improvement in communication ability to the GK12 programme; however, they did not present data to support this claim. We believe that the instrument we present here will provide a means for studying such questions.

Assuming that their subject matter knowledge is already strong as graduate students, spending a year in K12 classrooms provides scientists in the GK12 programme with teaching experience they might not get otherwise. However, the ability to quantify the impact of the GK12 experience on the fellows' communication skills, to teach communication skills to future scientists, and to identify areas of strength and areas that need improvement, have been hindered by a lack of appropriate evaluation instruments. This, together with the finding about GK12 fellows' increased ability to communicate their research, is what motivated us to explore how scientists explain their research.

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Background

The rubric is a description of how scientists explain their research. Because it is difficult to separate explanation from a deliberate attempt to teach, the development of the rubric draws on literature characterising how science is explained and the types of knowledge that teachers possess. Therefore, research on effective teaching methods sheds light on and is related to effective explanations.

Research on Explaining Science

The explanation of science has been studied extensively (Gopnik, 1996; Gopnik & Meltzoff, 1997; Hempel, 1965; Keil & Wilson, 2000; McCauley, 2000; Schank, 1986; Simon, 2000). Researchers have found similarities between how scientists explain science and how the general public explains science (Brewer, Chinn, & Samarapungavan, 1998). Similarities have also been found between how scientists and children explain various phenomena (Gopnik & Meltzoff, 1997). Both groups theorise about the phenomena they encounter. These theories help them explain the world. They rely on evidence in order to evaluate their theories, and these theories are constantly changing. Also, both scientists and the general public have been found to use the same frameworks when explaining phenomena: causal/mechanical, functional, and intentional.

Much of this research focuses on cognitive operations that scientists and the general public rely on as they attempt to explain phenomena that they do not yet fully understand. In the process of teaching science, however, teachers are expected to explain phenomena that they do understand. This is a significant difference because, when teaching, understanding must come before explanation, in that one must understand something before explaining it, either to oneself or to others (Keil & Wilson, 2000). In fact, the ability to explain one's understanding is often a measure of whether or not that thing has been effectively learned (Vygotsky, 1986).

Science teachers have been found to exhibit a different set of cognitive operations when explaining science to students. A group of researchers in England (Ogborn, Kress, Martins, & McGillicuddy, 1996) found that effective science teaching is carried out through a set of concrete practises that can be broken down and studied individually. Science teachers create a need for an explanation. They do this by relating ideas that are familiar to students to ideas that are unfamiliar to them, often through the use of analogies and stories. The science teacher must learn how to scaffold his or her explanations so that they build on and connect to each other across various lessons. Science teachers also rely on diagrams and gestures to aid in their explanations.

Research on the Types of Knowledge Teachers Possess

Three types of knowledge that teachers possess have been identified in the research literature: pedagogical knowledge, content knowledge, and pedagogical content knowledge (PCK).

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Pedagogical knowledge. Four pedagogical practises have been identified as key to enhancing learning: structuring the content in a clear and focused manner, awareness of students' prior knowledge, the ability to monitor student learning and provide relevant feedback, and building in appropriate amounts of time for students to practise what they are learning (Brophy & Good, 1986; Morine-Dershimer & Kent, 1999). The first three are also related to effective explanations.

A well-organised presentation is more likely to result in understanding. Findings from cognitive science and brain research (Donovan, Bransford, & Pellegrino, 1999) indicate that establishing clear shared goals for learning helps people learn by orienting their attention. Marzano, Pickering, and Pollack (2001), in a meta-study review of thousands of research studies into instructional practice, not surprisingly found that setting clear objectives was one of nine instructional strategies that significantly increases student achievement (by an average of 0.61 effect sizes, or a 23-point percentile gain, between experiment and control groups in these studies). Organisational structures that incorporate repetition of information (e.g., introduction–body–conclusion interpreted as 'tell them what you're going to tell them, tell them, then tell them what you told them') are more effective than those that do not (deWinstanley & Bjork, 2002). Science explanations are more effective when they have strong structure, and when learning goals are clearly communicated to the audience.

There are as many effective presentation methods as there are scientists. Some use humour to engage an audience, others engage by charismatic presence, and still others use voice inflections and body language. Marzano et al. (2001) derive that interaction with the audience is key to effective instruction. In particular, asking questions to elicit prior understanding before presenting new content, and linking to what the audience already knows, have been demonstrated to increase student achievement by an average of 0.59 effect sizes, or 22 percentile points (derived from synthesis of over 1200 studies). During an explanation, the audience must divide its attention between verbal and visual information (deWinstanley & Bjork, 2002); other activities (such as thinking about irrelevant ideas) also compete for the attention of individuals in the audience. Technical use of media can contribute positively to student learning. Mental imagery is a powerful learning tool (Bellezza, 1996), and media usage that assists in providing this imagery, without presenting unnecessary distractions that divide attention, is an effective way of communicating mental images. A presenter's choice of language also impacts the effectiveness of a presentation, particularly with audiences whose first language is not English (Adger, Snow, & Christian, 2002).

Content knowledge. The extent of an explainer's knowledge of the topic influences the quality of the explanation. The importance of subject matter or content knowledge for teaching has been well documented (Ferguson & Womack, 1993; Gess-Newsome, 1999; Grossman, Wilson, & Shulman, 1989; Guyton & Farokhi, 1978; Shulman, 1986). Teachers who have a conceptual understanding of the subject matter are better

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able to make connections between that subject matter and a student's prior knowledge (Hollon, Roth, & Anderson, 1991). They are better able to form relationships that assist in problem-solving when students become confused (Barba & Rubba, 1992).

The ways in which facts, concepts, and processes are stored mentally reveals the depth of knowledge a presenter has about the subject or research being explained. Research has demonstrated that those with deep and broad understanding of content store knowledge in specific ways. How knowledge is stored determines how a person breaks down the information being explained (Gagne & Glaser, 1987; Hiebert & Carpenter, 1992; Schwab, 1978; Strauss, Ravid, Magen, & Berliner, 1998). Those who are more knowledgeable break information into more coherent chunks because they better understand the connections between the discrete categories of knowledge they possess.

Furthermore, a significant body of research points to differences in how experts approach, process, and understand knowledge in their fields, and how they differ from novices in these respects (Donovan et al., 1999). Experts notice features and meaningful patterns that novices do not. Experts organise knowledge according to organising principles of the discipline, and their knowledge is contextualised to sets of circumstances. Effective explanation requires pointing out features and patterns, and articulating the organising principles and conditions associated with specific concepts or problems.

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Pedagogical content knowledge. PCK is defined as knowledge about how to teach a specific subject matter for improved understanding and learning (Shulman, 1987; Magnusson, Borko, & Krajcik, 1999). PCK is developed through the experience of teaching coupled with strong subject-matter knowledge (van Driel, Verloop, & de Vos, 1998).

PCK was originally described by Shulman (1986) as:

> the most useful forms of [content] representation, … the most powerful analogies, illustrations, examples, explanations, and demonstrations—in a word, the ways of representing and formulating the subject that makes it comprehensible for others. … Pedagogical content knowledge also includes an understanding of what makes the learning of specific topics easy or difficult; the conceptions and preconceptions that students of different ages and backgrounds bring with them to the learning of those most frequently taught topics and lessons. (p. 9)

In a later paper, Shulman (1987, p. 8) further clarified that 'it represents the blending of content and pedagogy into an understanding of how particular topics, problems, or issues are organised, represented, and adapted to diverse interests and abilities of learners, and presented for instruction'.

PCK as an aspect of teacher knowledge has been very difficult to capture through the research process (Lederman & Gess-Newsome, 1992; Loughran, Mulhall, & Berry, 2004; van Driel et al., 1998). While widely acknowledged as significant and necessary to teaching effectively, the substance of PCK in specific fields is not well defined (Loughran et al., 2004; van Driel et al., 1999), and even more difficult to measure

(Baxter & Lederman, 1999), primarily because its nature depends upon so many things, including the context and the discipline (Morine-Dershimer & Kent, 1999). PCK as a construct, as Gess-Newsome (1999) points out, has 'fuzzy boundaries'.

Aim of the Study

The rubric presented here was developed as part of a larger study of how scientists improve in their abilities to explain science over the course of a year's involvement in our GK12 programme. In the larger study, we compared the explanations of science graduate students' own research given prior to their involvement in the GK12 programme to explanations given after 1 year of involvement. This rubric was developed to evaluate the quality of explanations of scientific research by GK12 fellows to a general audience. The literature revealed that there are unique components to teacher knowledge. Therefore, we hypothesised that there may be unique components to scientific explanations, that they can be identified, and that the quality of these components can be judged in the context of the entire explanation. To this end, we asked the following questions:

1. What are the components of an effective scientific explanation?
2. Can the quality of an individual component be measured?
3. How do the components contribute to the effectiveness of the explanation?

Research Design

Thirty-two science graduate students, at various stages of their Master's or PhD programmes, participated in this study. Graduate students from across all science departments were represented in the study. The sample was opportunistic because it only included students in the GK12 programme. Students were asked *impromptu* to 'explain your own research to an audience of non-scientists in three to five minutes'. We used impromptu presentations for two reasons: to aid the purposes of the research, and to benefit the participants themselves. Impromptu explanations have been shown to expose misconceptions in the knowledge base of the person giving the explanation (Miller, 1992). Impromptu explanations also allow others who are assessing them (teachers, for example) to better understand the presenters' thinking (Fennema et al., 1996). In this study, we sought to understand both the depth of knowledge and the thought processes that went into effective explanations of research, thus we reasoned that impromptu explanations would allow us to achieve these goals. In benefiting the participants, research has demonstrated that reflecting upon one's own impromptu explanations leads to deeper conceptual understanding as well as insight into the gaps in one's own knowledge base (Kagesten & Engelbrecht, 2006; Miller, 1992). We shall both discuss and demonstrate the implications of this in the discussion that follows.

Students gave their impromptu explanations while they were participating in a seminar that met 1 hr/week during the semester prior to their involvement in the GK12

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programme. They were asked to give their explanations in front of a class of middle-school students during the first week of the seminar. The exercise was unanticipated by the graduate students, giving them no chance to prepare. However, after we announced the activity, graduate students had the opportunity to decline (and some of them did); and those who presented, signed consent forms in advance that had been approved by the university's Institutional Review Board. The middle-school students were drawn from an after-school programme at the university called Urban Scholars. Students in this programme are regularly exposed to university faculty and graduate students presenting about their research, in both formal contexts (such as lectures) and informal contexts (such as laboratory tours). The middle-school students took the opportunity at the end of each presentation to ask the graduate students questions and clarify any confusion they encountered. This opportunity was important because it gave the graduate students the chance to clarify parts of their explanations that were not clear, or to clarify the middle-school students' understandings based on what they had heard. However, this practise could be questioned on two counts: because it is still possible that middle-school students could have taken away some incorrect science, and because graduate students most probably would have provided clearer explanations had they had the opportunity to prepare their presentations. Others wishing to replicate this work may want to consider these factors.

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Development and Application of the Rubric

Both videos and transcripts of the graduate students' explanations were used to develop the rubric. We initially coded the data with key concepts from the research literature on explaining science. We then developed categories to organise these concepts. The videos and transcripts were coded for the prevalence of these concepts. We were looking for those concepts that exemplified effective scientific explanations.

At first we worked exclusively with the videos. In order to determine whether there were discernable patterns in the ways in which the graduate students explained their research, the videos were coded for the discrete activities in which science teachers engage when explaining science, as reviewed in the Research on Explaining Science section above. We grouped these activities into five categories (see Table 1).

We then turned to the transcripts that provided us with the opportunity to code for deeper analysis. With the transcripts, we initially focused on the five categories in Table 1. However, the closer analysis that the transcripts afforded allowed us to identify the amount and accuracy of the science contained in the explanations, and the specific pedagogical skills the scientists used in an attempt to aid the understanding of their audience, which in this case was middle-school students. A third observation emerged from this closer analysis: some scientists integrated pedagogical skill with content knowledge in superior ways.

Based on this analysis, we turned to the development of the rubric. We did this because at this point our analysis revealed that key characteristics of effective scientific explanations could be identified within the data. We developed the rubric into three categories with descriptions of performance levels (see Table 2): pedagogical

Table 1. Codes and categories used in the initial rubric

Overarching categories	Activities coded for
(1) Engaging the audience (2) Connecting to prior understanding (3) Structuring the explanation (4) Forming images (5) Presentation style	• Asking questions • Use of pictures to illustrate concepts • Use of demonstrations • Judging the audience's understanding • Identifying differences between how things appear and how they really are • Placing the research in the context of the larger picture • Explicit structure • Mental images • Using examples • Telling stories • Voice • Eye contact • Body language • Choice of words • Physical gestures • Use of media

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knowledge, content knowledge, and integration of the two in the service of a clear explanation. Specifically, the rubric assesses the methods scientists employ to communicate their knowledge orally to an audience in real time. We define pedagogy as the knowledge and skill involved in explaining major principles and concepts on which an individual's research rests. Content refers not only to factual knowledge and scientific processes, but also to how well the explainer understands those facts and processes in broader contexts. Here, we are concerned with accuracy and depth, including how the scientist portrays the overall organisation of knowledge. The last area assesses the ability to integrate these two knowledge bases in the service of a clear, coherent, and engaging explanation of scientific research.

This rubric was developed on a data-set consisting of approximately one-half of the videos collected over a 4-year period. Inter-rater reliability was measured twice. In the first instance, an environmental science professor applied the initial rubric to the entire first data-set. His ratings were consistent with those of the authors. In the second instance, a science educator who was trained as a research biologist applied the rubric to a subset of the first data-set. Validity of the rubric was checked by applying it to the other half of the videos. We found the rubric to be consistently comprehensive in analysing this second set of videos.

The three components of the rubric and their subcategories are explicated as follows:

- *Pedagogical knowledge*. In our observations of the science graduate students explaining their research, we have identified four aspects of pedagogical knowledge that aid the explanation of scientific research: structure and balance, response to the audience, choice of language, and technical skill in using media. These four

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Table 2(a). Rubric for evaluating 'pedagogical elements' (in videos of science graduate students explaining their own research to a general audience of non-scientists)

Pedagogy				
	Score			
Quality	Application of appropriate pedagogical elements is consistent	Application of appropriate pedagogical elements is present but inconsistent	Application of pedagogical elements is emerging but inadequate	Application of pedagogical elements not apparent
Structure and balance	• Explanation has a coherent structure that is explicitly laid out at the beginning and that flows conceptually from the simple to the more complex; clear connections are made between various parts of the explanation. • Demonstrates a good balance between the parts of the explanation, i.e., introduction, science, examples, conclusion, etc.	• Explicit structure of the presentation is established at the outset but not followed consistently OR a structure is used but not laid out in the beginning. Explanation is structured but the flow is interrupted by asides and misplaced examples; it is not always clear how parts of the explanation relate to each other.	• Explanation is structured at the outset but the structure falls apart; explanation has some unplanned structure; there are no clear connections between parts. • Presentation is unbalanced.	• Explanation lacks a coherent structure causing confusion.
Response to audience	• Looks for cues from audience, acknowledges cues, adapts explanation as necessary in response to cues. • Asks questions, reflects audience's answers in explanations in response.	• Looks to audience for cues and awkwardly attempts to adapt explanation. • Asks questions of audience, but does not incorporate answers into explanation. • Attempts to elicit prior understandings, but does not build explanation upon those understandings.	• Looks to audience for cues, but then ignores cues; misses obvious opportunities to incorporate audience's cues. • Asks rhetorical questions, not directed to audience. • Assumes prior understandings on part of audience that are incorrect and/or wildly varied.	• Doesn't look to audience at all for cues. • Asks no questions of audience. • Makes no attempt to connect to audience's prior understandings (neither perceived nor assumed).

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Table 2(a). *(Continued)*

Pedagogy				
	Score			
Quality	Application of appropriate pedagogical elements is consistent	Application of appropriate pedagogical elements is present but inconsistent	Application of pedagogical elements is emerging but inadequate	Application of pedagogical elements not apparent
	• Asks questions to elicit prior understandings, builds explanations on prior understandings, uses explicit examples audience is familiar with. • Incorporates knowledge of audience, what they already know (content), how they think (developmental), in structure of explanation.	• Incorporates knowledge of audience, but only in terms of what they already know (content) OR how they think (developmental) but not both.	• Perceives level of knowledge of audience and how they think but assumes a level that is too high or too low.	• Assumes incorrect level of audience's knowledge and how they think.
Clear choice of language	• Language is used at the appropriate level of understanding for the audience; it is unambiguous and concise; terminology is clearly defined.	• Language chosen is often used at the appropriate level of understanding, but there are occasional uses of language that is too technical, and some terminology is not defined.	• Language chosen vacillates between every day language and technical language causing some confusion; terminology is not defined.	• Language chosen is inappropriate for the audience; terminology is not defined; explanations are ambiguous and confusing.
Skill of presentation (technical use of media)	• Use of media clearly aids audience understanding of the explanation; the media are uncluttered, provide main points, are well structured, and assist audience in following presentation.	• Use of media provides some structure and assistance to the audience in aiding understanding but there are clear areas for improvement.	• Media are used to a limited extent and/or are of limited utility to audience in comprehending the presentation.	• No use of media OR use of media distracts from the presentation and confuses audience understanding.

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Table 2(b). Rubric for evaluating 'content knowledge' (demonstrated in videos of science graduate students explaining their own research to a general audience of non-scientists)

Content Knowledge

Quality	Score			
	Sophisticated level of content knowledge	Sufficient level of content knowledge	Poorly connected content knowledge	Weak level of content knowledge
Factual knowledge	• Presents scientifically correct content. • Shows evidence of a wealth of scientific factual knowledge.	• Presents mostly correct content with a few minor errors or omissions. • Shows evidence of scientific factual knowledge.	• Presents some correct and some incorrect content. • Evidence of limit to the extent of factual knowledge.	• Presents scientifically incorrect content. • Shows little or no factual knowledge.
How knowledge is understood	• States guiding principles clearly and concisely. • Clearly identifies relevant features and patterns in data or concepts. • Does not present confounding of superfluous concepts.	• Exhibits evidence of significant understanding of guiding principles but they are not presented clearly. • Identifies mostly correct features and patterns, but some are not relevant. • Presents a few themes or guiding principles that are not essential to central understanding.	• Presents themes of knowledge, not synthesized into guiding principles. • Attempts to identify features and patterns in data or concepts, but most are irrelevant or incorrect. • Presents superfluous themes of knowledge.	• Presents knowledge in a disjointed manner. • Apparently unaware of features and patterns in data or concepts. • Presents superfluous information that confounds the audience.

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Table 2(b). *(Continued)*

Content Knowledge

Quality	Score			
	Sophisticated level of content knowledge	Sufficient level of content knowledge	Poorly connected content knowledge	Weak level of content knowledge
Ability to transfer knowledge to broader contexts	• Presents examples of concepts applied to a variety of appropriate and important contexts. • Evidence of awareness of conditions associated with specific problems or concepts, and how topic presented relates to other knowledge. • Shows links between examples and topic of presentation. • Engages a diverse audience with the examples presented.	• Presents a few examples of knowledge transferred to different contexts. • Exhibits incomplete understanding of conditions associated with specific problems or concepts presented, and how topic presented relates to other knowledge. • Shows links between examples and topic of presentation. • Engages most of the audience with examples presented.	• Presents one example of knowledge transferred to a new context. • Aware of some conditions associated with specific problems or concepts presented, but does not connect these conditions with other knowledge. • Does not show links (or links not apparent) between examples and topic of presentation. • Cannot extend knowledge to contexts that engage some of the audience.	• Does not transfer knowledge to new contexts. • No evidence of awareness of conditions associated with specific problems or concepts presented, or how they are connected to other knowledge. • Cannot supply examples that engage the audience. • Cannot show relevance of knowledge to the audience.

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Table 2(c). Rubric for evaluating 'integration of content and pedagogy' (in videos of science graduate students explaining their own research to a general audience of non-scientists)

Integrated Content and Pedagogy

	Score			
Quality	Competent at integration of content and pedagogy	Developing ability to integrate content and pedagogy	Weak integration of content and pedagogy	No integration of content and pedagogy
Choice of presentation (tactical use of media)	• Makes choices of when to use different media for maximum impact to support effective explanation. • Draws from variety of media: chalkboard/whiteboard/PPT, humor, gestures, demonstrations.	• Use of media varies between appropriate and ineffective. • Takes opportunities to use media where other media would be more effective (e.g., draws on board instead of using manipulatives to represent things).	• Limited attempts to use media are of minimal utility in illustrating ideas. • Misses obvious opportunities to use available media to support explanations.	• No media used to support explanation.
Use of mental images to support explanation	• Varied and sufficient (not too much, not too little) approach to developing mental images through examples, case studies, stories, analogies, demonstrations, pictures drawn, concept maps/graphic organisers, and models. • Develops images that assist audience in understanding by providing resources for how to think about scientific phenomena explained or data presented (allowing audience to see it in researcher/expert's way rather than novice's).	• Limited use of mental images, some opportunities for developing mental images missed. • Develops mental images that are useful, but incomplete, in assisting audience with understanding concepts/ phenomena or interpreting data in the way researcher sees it. • Images have potential for being clear and powerful, but are not fully developed.	• Images presented distract from understanding scientific concepts or phenomena or data • Images are strictly language-based (no pictures or models). • Images developed are unfamiliar to audience and do not connect to prior understandings. • Ill-timed use of mental images, not in response to cues from audience.	• No use of mental images.

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Table 2(c). *(Continued)*

Integrated Content and Pedagogy

	Score			
Quality	Competent at integration of content and pedagogy	Developing ability to integrate content and pedagogy	Weak integration of content and pedagogy	No integration of content and pedagogy
Use of mental images to support explanation	• Presents clear, powerful images that are familiar to audience, connect to prior understandings, are both picture and language-based, and stick in audience's minds so they can refer back to them. • Carefully times when to use mental images to assist understanding, in response to cues from audience.	• Timing of use of mental images is mostly appropriate in response to audience's cues, but sometimes questions remain why certain images chosen.		
Scaffolding explanation	• Starts out at an appropriate level of comprehension. • Successfully builds understanding incrementally, step size is appropriate and audience is able to follow logical development of successively more complicated ideas. • Clearly points out differences between how things appear (what most people think) and how they really are (new knowledge gained through the research presented).	• Starts out with level of comprehension either slightly too high or too low. • Attempts to build understanding incrementally, but some step sizes are too large OR some steps are missing. • Points out what some may already know or think, but incompletely distinguishes between this and new knowledge gained through the research presented.	• Assumes too little or too much on the part of audience. Either starts too high, or ends too low (underestimating ability of audience). • Arguments are built logically, but not incrementally. Incremental building of understanding is evident in some cases, but not all, and step sizes between basic and advanced are too large to be of use to most of audience.	• Starts too high or ends too low. • No evidence of incremental building of understanding. • Makes no reference to organising principles of the discipline. • Does not identify relevant features and patterns in data or concepts. • Does not identify conditions associated with specific problems or concepts.

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Table 2(c). *(Continued)*

Integrated Content and Pedagogy

Quality	Score			
	Competent at integration of content and pedagogy	Developing ability to integrate content and pedagogy	Weak integration of content and pedagogy	No integration of content and pedagogy
	• Articulates clearly and refers to relevant organising principles of the discipline. • Points out relevant features and patterns in data and concepts in the service of understanding. • Clearly identifies conditions associated with specific problems or concepts. • Cause and effect, functionality, and/or intention frameworks are established where appropriate. Categories are explicit. Data or examples are used that support conclusions. Arguments follow a logical progression.	• Makes reference to relevant organising principles of the discipline, but not clearly articulated. • Makes reference to features and patterns, but does not consistently employ them in the service of understanding. • Incompletely identifies conditions associated with specific problems or concepts. • Some cause and effect, functionality, and/or intention frameworks are present, but the audience is left with questions as to how ideas and levels of comprehension relate. Categories are present but not clear. Data or examples are relevant to conclusions, but connections are missing or not specific enough. Some gaps exist in logic.	• Makes fuzzy reference to organising principles of the discipline, but not relevant or confusing. • Identifies some features and patterns, but misses most opportunities to employ them in the service of understanding. • Identifies only very few conditions associated with specific problems or concepts. • Implies but doesn't point out what some people may already know or think, but does point out difference between this and how things really are. • Cause and effect, functionality, and/or intention frameworks are present but not delineated. Categories are nonsensical. Data shown, or examples given, do not have clear relevance to conclusions presented. Logic and thoughts are incomplete or unfinished.	• Makes no attempt to identify difference between how things appear to be and how they really are, and/or states incorrectly how things appear or are. • No logical progression evident.

subcategories are based on skills in three areas necessary for presenting coherently: planning, addressing prior understandings, and overall presentation skill. Structure describes the logic and flow of an explanation, while balance describes the time spent on each section of the explanation. Structure and balance are indicators of planning. An explanation that comes across as being well planned reveals a broad and deep understanding of one's research. Knowledge that prior understanding must be addressed in scientific explanation reveals the ability to place the research in a broader context, which again demonstrates a broad and deep understanding of the research. A presenter's response to the audience and the language used in a scientific explanation demonstrates whether the presenter can customise the explanation. Finally, overall presentation skill represents the *technical* aspects of using media to enhance an explanation, revealing one's knowledge of how to use various media. In our study, students did not have a chance to plan for the use of media. However, a chalkboard, an easel and markers, and other props were available to students to enhance their presentations if they so chose. *Tactical* use of media, when to use it and which media to use, involves the integration of pedagogical and content knowledge and will be discussed under that category.

- *Content knowledge.* Three aspects of content knowledge are assessed through this rubric: factual knowledge, how knowledge is organised, and the ability to transfer knowledge to broader contexts. These three aspects of content knowledge are evidenced by facility with many facts about the research, breaking concepts down clearly, and using the knowledge in many contexts. This evidence provides us with three ways to assess the content understanding that is necessary for effective scientific explanation.
- *Integration of pedagogical and content knowledge.* Whereas the first two components of the rubric reveal the underlying knowledge base drawn upon in order to explain and present the science, this section of the rubric reveals the extent of a presenter's ability to place research in varied contexts. When a presenter can extrapolate research to various contexts, he or she is able to provide richer explanations. This is necessary for research scientists who want to disseminate their ideas broadly and for science teachers to enhance learning for diverse student bodies. Three subcategories in this section of the rubric—using mental images to support one's explanation, tactical use of media, and scaffolding explanations—require integrating pedagogical and content knowledge. Each subcategory involves the use of examples; that is, mental images that support a scientific explanation. In order to choose which mental images to use during an explanation, one must understand research in a particular context. Scaffolding involves weaving examples together to build an explanation. Effective science explanations are characterised by story-like presentations that involve mental images. The ability to form mental images is crucial to effective integration of pedagogy and content. Mental images assist the audience in understanding because they provide resources for how to think about scientific phenomena (Ogborn et al., 1996). Mechanisms for developing mental images include case studies, analogies,

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metaphors, demonstrations, pictures drawn or shown, concept maps and other graphic organisers, simulations, and models. These mechanisms for developing mental images provide models of how things work—they are important to scientific explanation because science is fundamentally about how things work. Prior knowledge involves often pervasive models of how things work, so the hardest part about explaining science is modifying, and even changing, the models that exist in people's minds about how the world works. Developing scientific understanding by story-like explanation is powerful and informative because it builds on prior understanding, connects to what is familiar, and leaves enduring mental images that aid learning and understanding.

Applying the Rubric

In this section we present three examples of GK12 fellows (science graduate students) attempting to explain their research to a general audience of non-scientists. These examples demonstrate how the three sections of the rubric—pedagogy, content, and the integration of the two—allow an evaluator to assess the quality of scientific explanations more fully.

Example #1. In this first example (see Table 3), the explainer has a strong understanding of the science behind his or her research, but weaker pedagogical skills in presenting that research.

This example allows us to understand how weak pedagogical knowledge impacts an explanation of scientific research. It is clear from lines 3–5 that the explainer understands the need for structuring the explanation; however, once he/she begins describing the science, he/she is unable to adhere to the structure that is laid out. The explainer jumps between everyday and technical language, which reflects misjudgement of the level of understanding of the audience.

The content in this explanation is scientifically correct in terms of factual knowledge. Scientific terminology is correctly used. It is also clear that the knowledge presented here is organised expertly. The explainer makes this clear by how he/she connects the explanation to the context. Evidence appears in line 17, with the key 'so that'. This is where the explanation connects to the chemistry organising principle that molecular structure informs a material's properties. The explainer also understands how the science that he/she is studying connects to other areas of science. This is evidenced by two examples. First, he/she understands the relevance of the science. In lines 18–21 he/she clearly explains how this research will change how chemicals could be manufactured differently so that they have different properties. Second, he/she understands that what he/she does is connected to other areas of science, and understands enough about those other areas to make the connections. In the parenthetical clause in line 20, he/she states that this will occur 'hopefully by natural enzymes and bacteria'. Had he/she not understood this, he/she would have been unable to state this clause.

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Table 3. Example #1: strong science content knowledge but weaker pedagogical knowledge

Line	Transcribed explanation	Visuals
1.	I am involved in green chemistry, which is involved in making	
2.	chemistry more environmentally friendly by producing less waste and less	*Moving hands back and forth*
3.	byproducts and reactions. So what I am working on is … I am going to	
4.	give you the big picture and then I am going to go back to simplify a little	*Opens hands outward then inward*
5.	bit. Um, I am trying to make a biodegradable plastic. Right now what is	*Holds up a plastic bottle*
6.	going on is they have biodegradable plastics out there, but the problem is	
7.	that you have your polymers, poly meaning many and mono meaning one,	*Both hands to left (many), both hands to right (one)*
8.	molecules so you have many molecules making up the plastic. And what	*Holds up bottle again*
9.	they do is take biodegradable constituents and put them on the plastic	*Holds hands around imaginary basketball*
10.	molecules and put it into plastic. The problem with it is—what happens	*Holds up bottle again*
11.	is it goes into the landfills and the biodegradable substituents are the ones	*Circles hands to emphasise syllables*
12.	that actually biodegrade. So what you are left with is the polymers and	
13.	plastics in the landfills. They don't actually go away. You just don't see	
14.	them anymore. So what I am trying to do is make a biodegradable	*Hits hands together on 'biodegradable'*
15.	backbone, something like starch or cellulose and put a substituent on the	*Counts on fingers to emphasise 'starch' and 'cellulose'*
16.	backbone and then that substituent will actually act as a binding agent	*Waves hands along line on 'backbone'*
17.	and lock these molecules together so that it will be able to be molded,	*Clasps wrists with both hands on 'lock'*
18.	formed and used. And then what will happen after it has been used—it	*Holds up bottle again*
19.	will be thrown into the landfills or wherever it needs to go, and when it	
20.	starts to biodegrade, hopefully by natural enzymes and bacteria, what we	*Counts on fingers to emphasise syllables*
21.	will be left with is CO_2 and water.	*Counts on fingers to emphasise CO_2, water*

The explainer's hand gestures are helpful when he/she is setting up the explanation, but once he/she transitions into explaining the science, the hand gestures become disconnected from what is being said and no longer assist the audience in understanding the concepts. It is interesting to note that some hand gestures are helpful, such as the locking wrists in line 17 and the backbone hand wave in line 16, if one already understands the science, because these movements refer to visualisation of the polymer molecules. However, for a general audience of non-scientists, these gestures are unhelpful at best and distracting at worst.

In this explanation, pedagogy and content are not integrated. The explainer uses no visuals or examples, which limits formation of mental images. It also inhibits the ability to scaffold the explanation for the audience; that is, to weave together examples to build understanding. This explainer starts at a low level, with definitions, and then makes a large step to advanced material without providing any scaffolding to connect the definitions to the science. This example demonstrates how weakness in pedagogy manifests in lack of integration.

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Example #2. In this next example (see Table 4), the explainer has strong pedagogical knowledge but lacks a full understanding of the scientific content behind the explanation.

This explainer starts out by providing a visual image and telling a story about how water flows from rivers to estuaries to the ocean. This story makes it clear to the audience how fresh and salt water mix in the estuaries, which motivates the point that studying the organisms occupying the estuary is significant. This is an example of sequencing information in a logically structured way. It also contributes to a plan for the explanation. It is clear that the story builds towards an explanation. This story leads the audience nicely into the actual content of the explanation.

However, when the explainer begins discussing the research in the context of estuaries, the explanation becomes difficult to follow. This happens for a number of reasons that are explicated by the rubric. It is clear that the explainer possess some facts about the research, but those facts are disjointed and not held together by clearly articulated guiding principles. This is illustrated in lines 10–12 by how the explanation becomes simply a string of unconnected facts. Those facts include: plantains live in estuaries, plantains use carbon to grow and multiply, plantains are eaten by fish, and so on. If this explainer had stronger knowledge of the content, he/she would have been able to explain why studying the effects of exposure to sun by food would have an impact on animals and organisms that live in the ocean, thereby making the science more relevant.

The hand gestures here indicate deeper understanding that is scientifically correct and related to the research, but what he/she says verbally does not explain the science well. In line 12, when referring to trophic levels, hand gestures indicate ladder rungs, but what is said is that plantains 'travel up through different levels of animals', which is unclear and inaccurate. In line 16, when explaining the carbon cycle, he/she indicates a circle but only explains that the carbon is being made into a

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Table 4. Example #2: strong science pedagogical knowledge but weaker content knowledge

Line	Transcribed explanation	Visuals
1.	I am a graduate student and my research [is] focused on areas called	
2.	estuaries. So if you got a coastline such as this	*Draws wiggly line going upward on board*
3.	and these coastlines have rivers that empty out into them. And	*Draws river coming out of wiggly coastline*
4.	then lining these areas are these places called estuaries, and these are	*Highlights edges of river near coastline*
5.	areas where you have salt water from the ocean that come in and meet	*Draws arrow showing path of salt water up river*
6.	the fresh water or water that doesn't have a lot of salt in it coming out	*Draws arrow showing path other direction starting from other end of river*
7.	this way. And in the estuaries you have different types of plants that are	*Draws X in estuary*
8.	used to dealing with these different types of waters. And these plants	
9.	produce carbon and you can think of carbon as being food. Food for the	*Hand makes a cup on 'food'*
10.	different plantains which is a plant that lives in the water, so plantains can	*Grits teeth*
11.	use this carbon or food to grow and multiply, and these plantains are then	*Draws dots in estuary*
12.	eaten by fish so it travels up through different levels of animals. And	*Motions upward rungs of ladder*
13.	what I look at is, 'How much carbon do these plants produce and how does	*Retraces X*
14.	that food or carbon change over time?' It can be changed with exposure	*Raises hand*
15.	to the sun. And it can be changed with the bacteria in this water that can	*Points to estuary*
16.	change this carbon and make it into a different form, and that then will be	*Makes circling motion with hands*
17.	transported out into the ocean and it affects the different animals and	*Motions up river*
18.	organisms that live out in the water.	*Motions along coastline*

different form. These are two major organising principals of biology—the gestures indicate some knowledge of these organising principles, but he/she is unable to explain these verbally.

As with the first example, the explanation of research here is not integrated. In this case, the explainer does not use the image he/she creates in a way that helps the audience understand the scientific phenomenon he/she is trying to explain. He/she paints the image effectively, but does not link it to the science. He/she is unable to scaffold the explanation because he/she does not weave together examples to build understanding incrementally.

Example #3. The example in Table 5 demonstrates an explanation that integrates pedagogy and content.

This explanation is logically structured; it flows from the simple to the more complex. The use of language and scientific terminology is appropriate. The explainer also builds the explanation on prior understanding and uses explicit examples with which the audience is familiar (i.e., fillings). He/she also uses voice inflections and hand gestures to very clearly emphasise the most important points.

The factual knowledge is correct, and is organised in a way that illustrates that the explainer has a clear command of the guiding principles behind the research. In this case, the guiding principle involves the flow of matter in cycles on earth and how conservation of matter is tantamount to that flow. This principle is demonstrated in lines 10–13 when he/she describes mercury going down the drain and out to the treatment works, and then removing the mercury using separators. The explanation also speaks to the broader context of how science and economics are integrated in the quest to determine whether and how to remove mercury from the cycle so that it does not pollute the water.

In this example, there is consistency between hand gestures and what he/she is saying. The hand gestures do not always aid understanding, but, unlike the other two examples, they are consistent with the explanation.

Most interesting to note is that there is no clear transition between setting up the explanation and the explanation itself, as in the other two examples. This explainer has thoroughly integrated the science with the pedagogy through scaffolding.

Using the Rubric to Assess Scientific Explanations

In our preliminary applications of this rubric, we discovered that there are three ways to apply it in assessing scientific explanations. First, one can evaluate an explanation as it is being given, in which case there is only one chance to apply the rubric. Second, one can videotape the explanation and evaluate the video, providing multiple opportunities for viewing. Last, one can use a transcript with the video as we did here. This application makes the structure of the explanation most evident. We have developed specific recommendations depending upon how the rubric is being used.

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Table 5. Example #3: strong content and pedagogical knowledge, and strong integration of the two

Line	Transcribed explanation	Visuals[a]
1.	I am studying mercury. Now particularly, I am looking at pollution	
2.	prevention. And we have all heard of pollution. We see air pollution; we	*Throws hands upward on 'air'*
3.	see smoke coming out into the air. Or land pollution you go to a landfill	*Raises hands high, makes circle motion on 'smoke'*
4.	and see all the stuff there in tires or leaky drums. What I am actually	*Scrunches up face on 'leaky drums'*
5.	looking at is water pollution. Particularly the pollution that goes to the	*Hands in front make wide circle*
6.	local treatment works called MWRA. I want you all to open your mouths	*Points to people*
7.	and turn to your neighbors. You see those gray fillings in your mouth?	*Points at teeth in own mouth*
8.	Those are called amalgum fillings, and they are made of metals. The metal	
9.	that they are made of is called mercury. Mercury is very toxic and a very	*Scrunches up face on 'toxic'*
10.	dangerous material. When the dentist puts in a filling or takes one out,	*Hands gesture inward on 'puts in' and outward on 'takes one out'*
11.	some of that mercury goes down the drain and out to the treatment	*Motions with hand downward on 'drain' then outward*
12.	works. People have developed these boxes, these separators, that will	*Motions square box*
13.	remove that mercury so that it doesn't go to the treatment plant. And	
14.	what I am doing is I am looking at how well they work and whether or not	
15.	they are worth the money. Because when you go to the dentist, you	
16.	obviously, have to pay money and if we start using these separators, then	
17.	you will have to pay more money. And I am looking at whether the	
18.	amount of mercury they remove is worth the money. So it is a bit of	*Hand gesture outward on 'remove'*
19.	science, a bit of economics, um, but overall it is looking at whether we	
20.	want to remove this mercury using these boxes or find another way to	
21.	prevent the mercury from going out into the water.	

Note: [a]Whenever not illustrating something with hands, uses hands throughout video to emphasise syllables.

When using the rubric in real time, there should be a pre-assessment of the presenter's pedagogical skills and content knowledge, which could take the form of a self-assessment. If the assessment is being conducted by an instructor, that instructor most probably has read the student's paper and has a sense of the student's strengths in explaining science. The instructor and explainer could have an initial conversation about the area they would like to focus on when the rubric is being applied.

When using the rubric with a video, we recommend that, for the first viewing, the video be assessed holistically. The integration category of the rubric provides the best opportunity for a holistic assessment of the explainer's ability to integrate pedagogical skill and content knowledge. This assessment will reveal whether the explanation is weak in pedagogy or content. Then, the video can be reassessed and more deeply analysed in either of those areas.

Assessing the explanation via transcript provides the most comprehensive assessment of a person's abilities to explain scientific research. This method allows for coding of the transcript and close textual analysis to determine levels of ability and fluency in explaining the concepts behind the science. When assessing using the transcript, we also recommend including visuals, because they are often helpful in understanding mental images the explainer attempts to build.

Lastly, use of the rubric requires an understanding of the underlying principles of the discipline in order to be able to judge whether the explanation is effective, especially in the rubric categories of content knowledge and integrated content and pedagogy.

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Discussion

Not all science professors are innately effective at explaining science. In our experience in the USA, graduate schools that train scientists rarely provide those students coaching in how to teach science. Hence, as professors they begin teaching science at university with little training in pedagogy. There is ample motivation for improvement of science teaching at university, but arguably most important is the longevity of the difficulty of retaining students, particularly those from traditionally under-represented groups, in science programmes at university (Campbell et al., 2002).

This rubric can lead to improved science instruction because it describes scientific explanations in the same three-part structure that educators use to describe effective teaching: pedagogical knowledge, content knowledge, and PCK (Shulman, 1987). This is a departure from earlier work on effective scientific explanations (Ogborn et al., 1996) that describes scientific explanations in terms of teaching strategies, such as telling stories and forming mental images. In other words, the rubric now allows us to map the practice of explaining science onto current understanding of the interaction of pedagogy and content while teaching. This makes sense because teaching is a profession in which the practitioner, like a medical doctor, needs to be able to act immediately on content knowledge (Shulman, 2005). Thus, the rubric is useful not only for evaluating the effectiveness of a given science explanation, but also for preparing both scientists and science teachers to explain science more effectively. Additionally, in using the rubric in workshops we have presented for science graduate students to help them improve explanations of their research, we have found that impromptu explanations with their peers enables the students to identify strengths and weakness in their presentation skills as well as gaps in their understanding. Providing graduate students with the opportunity to analyse their presentations within the three-part structure of the rubric allows them to understand the relationship between the content and how they structure the explanation, which is PCK.

Characterising PCK is crucial to helping science teachers explain science more effectively. However, PCK itself is difficult to measure. There are varying conceptualisations of PCK and amendments and modifications to Shulman's (1986) original conception of PCK. We believe, based upon years of experience in teaching both chemistry and physics at middle school, high school, and university levels, and also researching student thinking and how students understand demonstrations in chemistry, is that the type of PCK that works for different fields of science is different because it depends on the organising principles of that field of science. This may help to explain our finding that integrated content and pedagogy depends first, and separately, on having both pedagogical and content knowledge. To illustrate this, we present examples from chemistry and physics. In chemistry, one of the important organising principles is viewing the behaviour of matter on three levels—macroscopic observable, particle level, and symbolic representation—and being able to translate back and forth between these levels while weaving an explanation. Reasoning in chemistry therefore requires many logical steps (causation) and conditionals (if … then). Because of this, reasoning maps (graphic organisers) work well as a PCK method for helping people understand explanations in chemistry. In physics, understanding kinematics relies heavily on 'intuition' that people develop based on prior experience with how objects behave when forces act on them. One of the organising principles in physics is that external forces cause objects to accelerate. The main reason people have difficulty understanding explanations in kinematics is that they have already developed naïve theories to explain phenomena they have experienced, and those theories are deeply rooted. Hence, PCK methods that work well for helping people understand explanations in physics include using discrepant events that expose these naïve theories so prior knowledge can be accessed (e.g., Champagne, Gunstone, & Klopfer, 1985) and drawing force lines with arrows so that people can visualise forces causing acceleration (e.g., Bonham, Deardorff, & Beichner, 2003).

In our research we found examples where science graduate students with no teaching experience were strong in all three categories of the rubric, including integrating content and pedagogy (i.e., section three of our rubric). This section in our rubric resembles what many researchers call PCK in the literature. The literature states that PCK is dependent on teaching experience and subject matter knowledge. Given this, our research raises the question of how did these students develop the PCK they demonstrate if they have no teaching experience? Perhaps,

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PCK is also a disposition. If this is so, it suggests the need for further reflection on whether PCK is integrative or transformative knowledge (Gess-Newsome, 1999).

Conclusion

Our rubric has wide applicability. We developed it for evaluating scientific explanations given by GK12 graduate students. Our original intent was to help scientists self-evaluate their own research presentations, work toward communicating their research more effectively, and engage in peer-evaluation of research presentations by science graduate students while training to improve research presentation abilities. Used as a training tool by scientists, it holds the promise of assisting them in improving scientific communication. In addition, prior studies have shown that their understanding is enhanced further if they are provided the opportunity to reflect upon transcripts of themselves explaining their research. Armed with greater understanding of how people understand new knowledge, ultimately scientists can realise the greater impact of conducting scientific research more effectively. The rubric can also help science professors diagnose their skill in presenting scientific content (i.e., in teaching science courses). In addition, the rubric can be useful in training science, technology, engineering, and mathematics professionals who are career changers to K12 science teaching. Finally, the rubric is useful as a training tool in preparing science teachers, because it offers a mechanism, based on how people learn, for combining subject matter knowledge with pedagogical training.

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