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Disciplinary literacies in STEM: what do undergraduates read, how do they read it, and can we teach scientific reading more effectively?

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ABSTRACT

There have been calls for Science Technology Engineering and Mathematics (STEM) education to become more interdisciplinary, reflecting the reality of contemporary research. However, communicating across disciplines is challenging. In this article, I explore what and how students read in the STEM disciplines. I provide an overview of key topics in literacy research, and discuss the disciplinary nature of literacy. I compare disciplinary literacy requirements in STEM through thematic analysis of UK quality subject benchmark statements, which identifies considerable variation in the expectations of undergraduates to engage with primary research literature. I explore implications this has for interdisciplinary teaching, and present some published pedagogical strategies for engaging students in research literature. I call on STEM educators to embed inclusive disciplinary literacy teaching within curricula to support students in their reading. I also highlight the need for clear understanding of disciplinary conventions and reading expectations when designing interdisciplinary educational programmes.

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Introduction

STEM research and careers are increasingly interdisciplinary, with individuals from different technical disciplines coming together to provide technological solutions to global problems (Davé et al., 2016). There has therefore been a move to reflect the interdisciplinary nature of STEM careers in undergraduate education (Madden et al., 2013; Manathunga & Brew, 2012). The Wakeham report into STEM degree provision in the UK highlighted a need for graduates to ‘communicate with, and feel comfortable working across, teams comprised colleagues from a range of disciplinary backgrounds’ (Wakeham, 2016). Interdisciplinary education may involve bringing together relatively similar subject areas, or may involve collaborations between the STEM disciplines and the social sciences, creative arts or business and enterprise (Capraro & Jones, 2013; Daugherty & Carter, 2018; Madden et al., 2013). However, working across disciplines is potentially challenging for both students and staff. Staff and students are generally

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more comfortable thinking within their disciplines than in a multidisciplinary or interdisciplinary way. Boud highlights that ‘there is no such thing as an interdisciplinary discipline’; students and staff approach interdisciplinary problems from their own subject area perspective (Boud, 2012). Golding and Baik note that ‘students tend to take the approach of one discipline or subject at a time and do not mix them.’ (Golding & Baik, 2012). We therefore need to be clear about the approaches and conventions of individual academic disciplines, and understand how these differ from other disciplines if we are to develop effective interdisciplinary education.

Becher’s classic text ‘Academic Tribes and Territories’ argues that the distinct nature of disciplines underpin behaviours and practices of staff, resulting in differences in academic cultures along disciplinary lines (Becher, 1989). Although we may instinctively recognise distinct disciplines, there is no single definition of an academic discipline (Trowler, 2012). Krishnan (2009) defines a discipline with reference to 6 shared characteristics, which include a body of accumulated specialist knowledge, theories and concepts through which specialist knowledge can be organised, and specific language and terminology. This definition implicitly places a heavy emphasis on the written literature of a discipline; in STEM our accumulated specialist knowledge is usually stored as either disciplinary textbooks or research papers. These texts describe the key ideas of the discipline, and use a characteristic set of technical terms and linguistic conventions. The body of written communication therefore represents one of the defining components of disciplinary thinking. This creates challenges for interdisciplinary working; communication within interdisciplinary teams has been highlighted as a significant challenge due to a lack of shared language and understanding of disciplinary conventions (Davé et al., 2016).

Higher education is partially characterised through students engaging with complex academic texts. It has been estimated that students spend between 7 and 14 hours a week reading academic material, representing a significant component of their studies (Huang, Capps, Blacklock, & Garza, 2014; St Clair-Thompson, Graham, & Marsham, 2017). However, reading academic texts is not easy. When designing curricula, we often overlook the inclusion of general skills training such as reading and critical thinking, focussing instead on factual content and technical skill development. We typically provide students with reading lists, but may fail to consider whether they have the skills to engage with the materials listed. This is particularly true within STEM disciplines; scientific text is characterised by being written in the abstract sense, being very concept dense and using high levels of technical terminology (Fang, 2005). These conventions and ways of writing differ between the STEM disciplines. To become a ‘biology graduate’ means learning a distinct set of written conventions that would be distinct from those in chemistry, let alone in arts or social sciences. This has significant implications for interdisciplinary education; learning to read and understand the norms of one discipline is challenging enough, let alone understanding conventions and communication styles of other disciplines.

Within this article, I argue that to develop the next generation of STEM graduates we need to pay more attention to how we teach technical reading skills. I explore the extent to which graduates from different STEM subjects can be expected to use the written literature of their discipline (with a particular focus

on original research literature), and what implications this has on interdisciplinary approaches to STEM education. I will highlight some key topics in literacy research, and also suggest some pedagogical strategies which may be of value to STEM educators introducing students to research literature. I will also consider the impact that disciplinary literacy has on interdisciplinary teaching, and whether students can meaningfully engage with complex text across disciplines. I also offer my own reflections on teaching using research literature, and suggest more effective approaches to engaging students with the requirements of academic reading.

What does literacy research tell us about the development of advanced reading skills?

Before discussing reading within the context of STEM education, I think it is valuable to consider what we know about the development of reading skills. There is a rich history of literacy research that scientific educators are mostly unaware of, but which has direct implications for the development of advanced reading skills within STEM. Here, I review some key ideas within literacy research that may be useful to STEM academics. This should not be taken as a comprehensive review of all literacy research which would be outside the scope of this review. For a primer on reading and comprehension, I direct readers to Harrison and Perry (2004) and O'Donnell and Wood (2004), on which much of the following is based.

Reading fluency and comprehension are distinct attributes

When we ask a student to read a text, we don't want them simply to recognise all the words within it. We want them to gain an understanding of the material described. It is important to distinguish between reading fluency (i.e. the ability to read quickly and accurately without paying conscious attention to individual words) and reading comprehension (i.e. the extraction of meaning from a text) (Harrison & Perry, 2004; O'Donnell & Wood, 2004). Comprehension is not a passive process; the reader must actively construct meaning from the text (Vacca & Vacca, 2002). Kintsch's 'Construction-Integration' model of learning separates comprehension into two phases; (i) identifying the words, vocabulary and grammatical features of the text, and (ii) integrating that knowledge into the reader's current mental model of the world (Kintsch, 1998). It is therefore not enough to assume that fluent readers have the skills and strategies to construct meaning, as these are two separate processes.

Comprehension is strongly affected by prior knowledge; in order to understand we must be able to link new information to existing information (Harrison & Perry, 2004; O'Donnell & Wood, 2004). If we only have highly fragmented or limited knowledge about a given topic, we cannot construct new meaning when reading. Schema theory posits that this prior information is organised within the brain into 'schemas', which are networks of related concepts (R. C. Anderson & Pearson, 1984). For example, a biologist might have a rich schema that relates to photosynthesis, which includes information about chloroplasts, chlorophyll and techniques used for studying photosynthesis. If someone with this schema (i.e.

a biologist) were to read a paper on a particular photosynthetic protein, they would have a body of organised knowledge that they could draw from. The biologist then adapts that schema to accommodate new information, therefore retaining it in their long-term memory. However, a psychologist may have a very limited schema relating to photosynthesis, so would be unable to derive much meaning from the paper, and would ultimately forget most of what they read.

There are many other factors that can impact on an individual's ability to comprehend text, including the reading situation, the experience and motivation of the reader, and the way that the text is structured and written (Harrison & Perry, 2004; O'Donnell & Wood, 2004). Many of these represent particular challenges for STEM disciplines. Scientific text is very concept-dense, uses highly specific terminology and the writing style may make the text extremely difficult to process (Fang, 2005). Equally, readers may have little or no experience in reading scientific text, are reading sources that they would not have chosen to read for themselves, and may not have sufficient reading fluency to be able to engage easily with the text (O'Donnell & Wood, 2004).

Learning to read is a life-long process

Most models of reading development have been developed in a school education context. However, some models also have relevance to the development of advanced literacy expected in a university context. One model that has value is Alexander's Model of Domain Learning (MDL) (Alexander, 1997, 2003, 2005). The MDL proposes that learning to read is a life-long process, and is divided into three

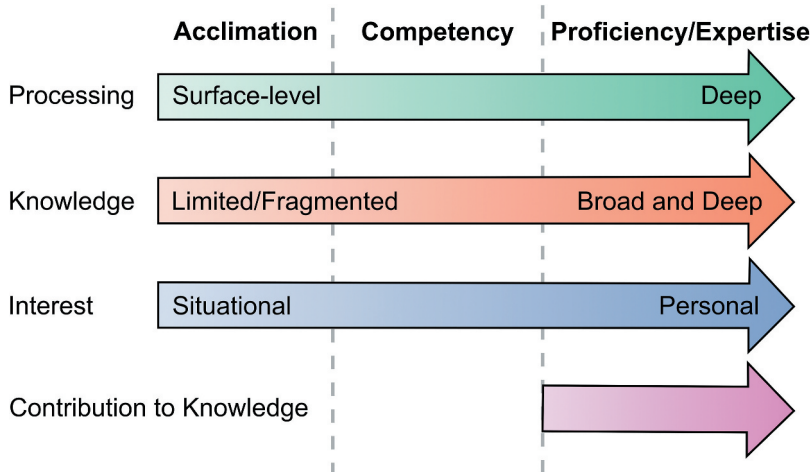


Figure 1. Alexander's model of domain learning (MDL). Reading development is presented as a life-long process, divided into three sequential phases of acclimation, competency and proficiency/expertise. These stages are associated with changes in processing strategies, extent of prior knowledge and motivation for reading (i.e. interest). Proficient/expert readers are also able to contribute new knowledge through critical evaluation or being able to write using the conventions of the discipline (Alexander 1999, 2003, 2005).

main phases (Figure 1). The first phase is ‘acclimation’, where readers are encountering unfamiliar texts for the first time. In this phase readers have a limited or fragmented body of knowledge (schema) on which to draw, and adopt relatively superficial processing strategies. Acclimating readers are likely to be reading the unfamiliar text because they are required to (e.g. to pass a test), therefore have situational interest in the source. As readers build experience, they pass into ‘competency’. Competent readers have a more coherent schema on which to draw, meaning that they can adopt more strategic processing of the text. Competency is associated with deeper processing skills, and with an increased level of personal interest. The final stage is ‘proficiency’, where readers have a broad and deep knowledge base on which to draw, and adopt deep processing strategies. Reading is highly likely to be motivated through personal interest. Proficient readers also create new knowledge through their analysis of the text, being able to adopt a critical standpoint on the material (Alexander, 1997, 2003, 2005). This model has been applied to studies of masters students encountering the literature (Lie, Abdullah, He, & Tour, 2016), and to evaluate the reading skills of undergraduates, postgraduates and researchers in the biosciences (Hubbard & Dunbar, 2017).

Reader identity and self-efficacy is important

When we read we are not machines, we are people. Our personal values and beliefs shape the way we read. For example, as a biologist I appreciate texts that set out information in a broadly factual way so that I can critically evaluate the claim, but I struggle to engage with more abstract literary forms such as poetry. My identity as a reader therefore shapes both the texts I choose to read, and the approach I use to read them. Hall defines reading identity as ‘how capable individuals believe they are in comprehending texts, the value they place on reading, and their understandings of what it means to be a particular type of reader within a given context’ (Hall, 2012). This links strongly with the concept of self-efficacy, defined as the belief an individual has in their ability to succeed (Bandura, 1977). Some students have self-beliefs that support their learning (e.g. I like to learn things; If I work hard I will succeed in my degree programme), but others have personal beliefs that undermine progress (e.g. I am not very good at school, I do not enjoy reading) (Buehl, 2017). Self-efficacy has been positively associated with reading and writing performance in a number of studies (McCarthy, Meier, & Rinderer, 1985; Meier, McCarthy, & Schmeck, 1984; Pajares, 1996; Pajares & Johnson, 1996; Shell, Colvin, & Bruning, 1995; Shell, Murphy, & Bruning, 1989). One study of psychology undergraduates indicated that students with high reading self-efficacy adopted deeper processing strategies while reading, and adopted more successful approaches to academic study (Mercè Prat-Sala & Redford, 2010). A follow-up study found that both reading and writing self-efficacy were positively associated with writing performance, therefore impacting on educational attainment (Mercè Prat-Sala & Redford, 2012). Buehl (2017) points out that a student who is struggling with academic reading may be a highly proficient reader in other formats (e.g. novels), so it may be their academic literacy

rather than absolute literacy level that is the barrier (Buehl, 2017). We should therefore be particularly mindful of those with low self-belief in their academic reading abilities, and may need to introduce support mechanisms to help these students.

Disciplinary literacy

When the word ‘literacy’ is used, we often think of general reading and writing skills that are developed in the early years of the school curriculum, which Shanahan and Shanahan (2008) refer to as ‘Basic’ and ‘Intermediate’ Literacy (Figure 1). These skills include the ability to decode individual words, understanding the conventions of written text, developing reading fluency and expansion of vocabulary (Buehl, 2017; T. Shanahan & Shanahan, 2008). However, when students encounter more complex subject-specific academic texts (e.g. textbooks) they start to specialise in their reading, and require more sophisticated processing abilities. There have been two schools of thought on whether the skills need to read academic texts are equivalent or differ across disciplines. ‘Content Area Literacy’ assumes that it is only the content of disciplinary texts that differ, whereas writing style is broadly consistent between discipline. This view infers that general literacy strategies (e.g. mind mapping, use of mnemonics) are sufficient to engage with disciplinary texts (Fang & Coatoam, 2013; T. Shanahan & Shanahan, 2012). In contrast, ‘disciplinary literacy’ recognises that there are specialist conventions within disciplines that need to be appreciated for a full understanding of a source (Buehl, 2017; Fang & Coatoam, 2013; Goldman et al., 2016; T. Shanahan & Shanahan, 2008, 2012). Disciplinary literacy can be defined as ‘understanding of both disciplinary content and disciplinary habits of mind (i.e. ways of reading, writing, viewing, speaking, thinking, reasoning and critiquing.’ (Fang & Coatoam, 2013). Crucially, these aspects of literacy are not the same in all academic disciplines. The strategies needed to understand and evaluate a biology source might be quite different to those needed in physics, let alone those needed in the social sciences or arts. As such, those who specialise in particular subject areas will develop their disciplinary literacies in an unequal way, becoming more proficient in understanding texts in some subject areas than in others (Figure 2).

Sophisticated disciplinary reading skills are rarely taught explicitly, but are of critical importance for students to approach texts within specialist topic areas (T. Shanahan & Shanahan, 2008). However, we tend to rely on ‘general’ literacy development within schools to underpin the reading skills needed for subject-specific teaching. This is potentially flawed. For example, many UK universities require at least a grade C in GCSE English for admittance on to STEM undergraduate programmes as a demonstration of literacy. It is highly unlikely that GCSE English will have addressed the conventions of scientific textbooks, let alone research-level reading materials. Similarly, international students studying in the UK may be required to demonstrate proficiency in English through taking a standardised test (e.g. International English Language Testing System), but this presents students with texts ‘selected for a non-specialist audience but are appropriate for people entering university courses or seeking professional registration.’

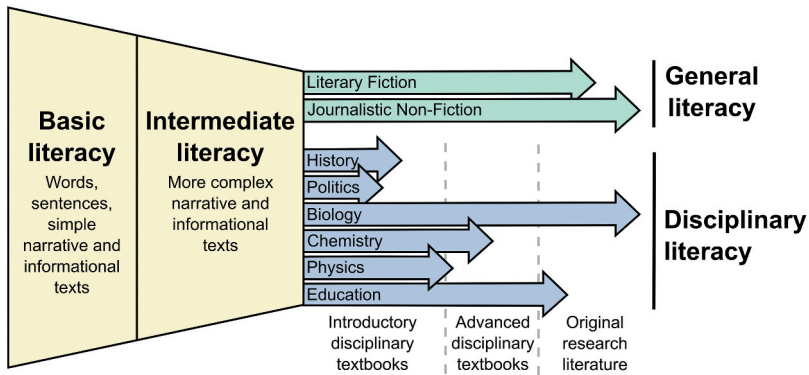


Figure 2. Increasing specialisation of literacy development, using my own disciplinary literacy profile as an example. Basic literacy development takes place in primary schools, and establishes a foundation for reading and writing. Intermediate literacy development is generally in upper primary/lower years secondary schools, where pupils encounter increasingly complex texts. Disciplinary literacies are established during secondary schools, where students start to use subject-specific textbooks, and continue into higher education and research careers, culminating in the use of original disciplinary research literature. My own disciplinary literacy profile is given as an example; as a biologist I am confident in reading original research literature in biology, but have less sophisticated literacy skills for the other STEM subjects, and even less for the humanities. Having recently specialised in biology education I engage with original educational research literature, but I am much less confident with this than with biological texts. Original model based on Shanahan and Shanahan (2008), figure adapted from Buehl (2017)

(‘IELTS test format,’ n.d.). Without specific teaching that addresses disciplinary literacy within university curricula, students may lack the skills needed for academic success and fall victim to the ‘hidden curriculum’ (Margolis, 2002). Buehl (2017) argues strongly that as disciplinary conventions are highly contextualised, they must be taught within the core curriculum by subject experts. Students should also be given repeated opportunities to practice their disciplinary literacy skills through an academic programme (Buehl, 2017).

A Thematic analysis of disciplinary literacies in the UK STEM undergraduate context

Most studies of disciplinary literacies focus on the differences between broad subject areas; for example, Shanahan et al. developed their thinking on disciplinary literacy by comparing the approaches of mathematicians, historians and chemists (C. Shanahan, Shanahan, & Misischia, 2011; T. Shanahan & Shanahan, 2008). However, there may be differences in conventions between scientific disciplines (e.g. chemistry vs biology), and even between sub-disciplines (e.g. molecular biology vs ecology). There may also be differences in the levels of disciplinary literacy expected within undergraduate curricula, particularly with respect to the types of text students are expected to engage with. For example, bioscience undergraduates might be expected to use original research literature in their first year

(Willmott, Clark, & Harrison, 2003), whereas undergraduate mathematician may not engage with research literature at all (Bruehl, Pan, & Ferrer-Vinent, 2015). However, a systematic consideration of these disciplinary literacy standards is absent from the literature. I therefore present an analysis of the ‘reading landscape’ of STEM undergraduate programmes in the UK below. In particular, I focus on the extent to which undergraduate students are expected to engage with original research papers.

Thematic analysis methodology

To gain an overview of the requirements for using research literature, I conducted thematic analysis of UK national benchmarking standards for STEM degree programmes. In the UK, all degrees are overseen by the Quality Assurance Agency for Higher Education (QAA). The QAA publish Subject Benchmark Statements (SBSs) for clusters of subjects, which contain indicative descriptions of the subject knowledge and key skills that a degree programme should include, and the expected abilities of graduates. These are typically expressed as ‘Threshold standards’ which reflect the expected capabilities of all graduates, and ‘Typical standards’ which a high achieving graduate would achieve (QAA, 2015b). While these documents are not intended to describe a prescriptive syllabus, they give a broad indication of the scope of programmes in a given subject area, and the typical skills that are developed within programmes. As these are available for all subject areas, these benchmark statements allow for comparison of educational practice between disciplines, and as such were used as the data source for the analysis. The following analysis is based on the most up-to-date SBS available for each subject at the time of the analysis.

Thematic analysis is a qualitative approach to identifying and reporting patterns or themes within a dataset, which can ‘highlight similarities and differences’ and ‘summarise key features of a large body of data’ (Braun & Clarke, 2006). Thematic analysis can be performed from an inductive or theory-driven perspective. Here, I adopt a theoretical approach based on Anderson and Krathwohl’s revised Bloom’s Taxonomy (L. W. Anderson & Krathwohl, 2001). To determine the disciplinary literacy requirements of each STEM subject, I assess each benchmark statement against two criteria; (i) is a requirement for using research literature included in the aims, knowledge and skills sections of the benchmark statement, and (ii) what are undergraduates required to be able to do with research literature?

To address question (i), I searched each SBS for statements that referred to the use of research literature. For consistency between disciplines, I only considered statements from the ‘Aims/Objectives’ and ‘Threshold/Typical standards’ sections, as these were consistently structured across the different SBS. An initial search through the SBS was conducted using the words ‘literature’, ‘sources’ and ‘read/reading’. Sentences containing these words added to a database. However, on re-reading the SBS I identified that while some SBSs explicitly refer to the use of scientific or published literature, this was more implicit in the phrasing of other statements. Phrases that were assumed to refer to published research literature included ‘*current developments at the frontiers of the subject*’ (Physics, Astronomy and Astrophysics) and ‘*limits of current hypotheses*’ (Biomedical Sciences). These sentences which implicitly referred to research literature were therefore

added to the database before analysis. After compiling this database, I first classified subjects on the basis of whether there was any reference to using research literature, and whether the Threshold/typical standards included a direct reference to use of research-level reading materials. This separated the subjects into three groups; subjects that did not mention use of research literature, those that mentioned it but did not specify use of research literature in the standards required, and those that did require undergraduates to engage with research literature.

To address question (ii), I considered those subjects which did make explicit reference to use of research literature in their expected standards. I use the verbs contained within the threshold standards section of the benchmark statement, and align these with the 6 categories of cognitive processing (remember, understand, apply, analyze, evaluate and create) of Anderson and Krathwohl (2001). As such, I was able to subdivide this category into subjects that require students to adopt 'higher level' processing (typically expressed as 'evaluate') and those that did not. As a result, the subjects were separated into four categories as described below. To validate the analysis, the database of statements and the category descriptions were provided to an independent researcher who confirmed that the classification was appropriate.

Thematic analysis results

Through a recursive process of reading, identifying similarities and differences between the subjects, re-reading and classifying, I identify four major categories of research literature use (Table 1). I present these in order of the demands placed on undergraduate students, from the lowest level of engagement with research literature to the most demanding. The four groups are defined as follows:

Group 1: Subjects which do not mention research literature

The first group of subjects makes no mention of research literature or a requirement for undergraduates to be reading at the cutting edge of the discipline. This group includes Computing and Mathematics, Statistics and Operational Research, where the benchmark statements emphasise numerical skills and problem-solving rather than the use of research literature.

Group 2: Subjects which include use of research literature in general aims, but not in benchmark standards

The second group of subjects discusses the use of research literature within the broad aims and skills section of the benchmark statement, but do not make an explicit requirement for undergraduates to use this literature within the threshold standards. This group is exemplified by Chemistry, which includes '*read and engage with scientific literature*' in the subject knowledge and understanding. The Typical Benchmark Standard for bachelor's level states that '*knowledge base covers essential aspects of subject matter dealt with in the programme and shows some evidence of enquiry beyond this*', but does not make a specific requirement for undergraduates to use research literature. This is reinforced by the description of integrated masters courses within the Chemistry SBS, where the threshold standard is '*knowledge base*

Table 1. Classification of STEM disciplines based on descriptions of expected use of research literature by undergraduates contained within QAA subject benchmark statements. references to specific statements within the SBS are given in square brackets.

Group	Description	Subject areas	Description in Aims/Subject Knowledge and Skills sections	Benchmark standard	Descriptor in Threshold Standards	Bloom's Taxonomy level of descriptor	Reference
Group 1	Do not mention use of research literature	Computing Mathematics, Statistics and Operational Research	- -	- -	- -	- -	QAA, 2016a QAA, 2015d
Group 2	Include use of research literature in general aims, but not in expected benchmark standards	Chemistry Forensic Science	Read and engage with scientific literature [4.2] Acquire research skills appropriate to degree-level study, with an appreciation of current and emerging research in forensic science and other relevant areas [3.1]	- -	- -	- -	QAA, 2014a QAA, 2012
Group 3	Undergraduates expected to use research literature	Engineering* Materials	N/A The ability to demonstrate critical thinking in reviewing the state of the art and in the analysis of experimental data both in isolation and in the context of the wider literature [3.8 ii]	N/A Threshold Typical Excellent †	Ability to use and apply information from technical literature (pg 14) A list of essential literature may be quoted without critical analysis. [5.1 iii] There is good understanding of literature and relevant practice with suggestions for future work. [5.2 iii] <i>There is clear evidence of critical thinking in the analysis and discussion of results, with excellent understanding of literature and of relevant practice. [5.3 iii]</i>	Apply Apply Apply Evaluate	QAA, 2015c; Engineering Council, 2014 QAA, 2017a
		Physics, Astronomy and Astrophysics	Programmes expose students to recent research in order to develop some qualitative understanding of current developments at the frontiers of the subject [3.5]	Typical	Management and use of research-based materials [5.5 v]	Apply	QAA, 2017b

(Continued)

Table 1. (Continued).

Group	Description	Subject areas	Description in Aims/Subject Knowledge and Skills sections	Benchmark standard	Descriptor in Threshold Standards	Bloom's Taxonomy level of descriptor	Reference
Group 4	Undergraduates expected to critically evaluate research literature	Biomedical Sciences	The ability to read and use appropriate literature with a full and critical understanding, while addressing such questions as content, context, aims, objectives, experimental design, methodology, data interpretation and application [5.3 iii]	Threshold	The ability to access and evaluate biomedical sciences information from a variety of sources and to communicate the principles both orally and in writing in a way that is organised and topical, and recognises the limits of current hypotheses [8.6 iv]The ability to assess the evidence base for scientific claims, by reading primary literature and commenting on the adequacy of the methods, data and interpretation [8.6 vii]	Evaluate	QAA, 2015a
		Biosciences	The ability to read and use appropriate literature with a full and critical understanding, while addressing such questions as content, context, aims, objectives, quality of information, and its interpretation and application [5.3 iii]	Threshold	The ability to access and evaluate bioscience information from a variety of sources and to communicate the principles both orally and in writing in a way that is organised and topical, and recognises the limits of current hypotheses [7.7 iv]	Evaluate	QAA, 2015b
		Earth Sciences, Environmental Sciences and Environmental Studies	Intellectual skills (knowledge and understanding) associated with subject specific theories, paradigms, concepts and principles [3.3]	Threshold	A critical approach to academic literature, data and other sources of information [5.1]	Evaluate	QAA, 2014b
		Psychology	Retrieve and organise information effectively. Psychology graduates are familiar with collecting and organising stored information found in library book and journal collections, and online, critically evaluating primary and secondary sources [4.5 iv]	Threshold	Demonstrate systematic knowledge and critical understanding of a range of influences on psychological functioning, how they are conceptualised across the core [skill areas] and how they interrelate [6.3 iii]Demonstrate detailed knowledge of several specialised areas and/or applications, some of which are at the cutting edge of research in the discipline [6.3 iv]	Evaluate	QAA, 2016b

* The Engineering subject benchmark statement does not contain descriptors of skills or benchmark statements, but instead refers to the Engineering Council Accreditation of Higher Education Programmes: UK Standard for Professional Engineering Competence. Descriptors are therefore taken from this document rather than the QAA subject benchmark statement, so do not include the 'Threshold/Typical' descriptors found in the other benchmark statements

† Most benchmark statements do not include an 'Excellent' category. Materials uses this benchmark, but it should not be assumed that other subjects do not expect excellent students to reach this level. For consistency, overall classification uses the threshold/typical descriptors.

extends to a systematic understanding and critical awareness of current research in the subject' (QAA, 2014a). For Chemistry, there is therefore a clear indication that use of published literature is only a requirement at masters level.

Group 3: Subjects which expect use of research literature

This group includes subjects which include the use of research literature in the aims and skills sections of the benchmark statement, and indicate that some engagement with the literature is expected to achieve the 'typical' standard. Physics, Astronomy and Astrophysics fall into this group. The Subject-specific knowledge and understanding section of the SBS states *'programmes expose students to recent research in order to develop some qualitative understanding of current developments at the frontiers of the subject.'* (QAA, 2017b). The requirements of the 'typical' benchmark standard are 'management and use of research-based materials', indicating physics undergraduates should engage with the literature, but critical evaluation is not required.

Group 4: Subjects which expect critical evaluation of research literature

This group of subject has the most demanding requirements for undergraduate engagement in the literature. Engagement with research literature is required at the 'threshold' level, i.e. is expected of all graduates, and there is a requirement for critical analysis of this material. This group is best represented by Biosciences. The core knowledge, understanding and skills section for Biosciences includes *'the ability to read and use appropriate literature with a full and critical understanding, while addressing such questions as content, context, aims, objectives, quality of information, and its interpretation and application'* (QAA, 2015b). Within the threshold standards, undergraduates are required to have *'the ability to access and evaluate bioscience information from a variety of sources and to communicate the principles both orally and in writing in a way that is organised and topical, and recognises the limits of current hypotheses'*. As such, undergraduates in these subject areas are expected to be reading critically at the cutting edge of the discipline.

Thematic analysis discussion

The analysis presented above indicates that there is a continuum of requirements for disciplinary literacy amongst the STEM disciplines in the UK undergraduate context (Figure 3). Subjects that place a high emphasis on numerical skill and/or problem-solving tend to have lower level requirements for using research literature (e.g. Maths, Computing, Chemistry). Programmes with higher level requirements for use of literature tend to emphasise evaluation and critical evaluation (e.g. Biosciences, Psychology, Earth Sciences) to reach an academic judgement on a particular topic. As such, the disciplines in Group 4 require undergraduates to be using research literature in a similar way to postgraduate students and researchers. It should be noted that the benchmark standards for the Group 4 subjects are extremely high. I question whether most researchers could genuinely claim to read all papers within their specialist field *'with a full and critical understanding, while addressing such questions as content, context, aims, objectives, quality of information,*

and its interpretation and application’, let alone whether we should expect all undergraduates to achieve this level of mastery.

While the analysis presented above provides an insight into the literacy requirements of UK STEM degrees, it should not be taken as an accurate description of all degree programmes. SBSs describe the requirements for a degree to be approved by the QAA, but are not intended as a curriculum. As such, many degree programmes will teach beyond what is implied by the SBS, and the analysis presented above should be regarded as ‘minimum’ expectations. It should also be noted that in the UK, many degrees are also accredited by Professional Societies (e.g. Royal Society of Chemistry [RSC], Institute of Physics etc.), which also have significant influence on undergraduate curricula. These may include requirements around the use of research literature; for example, the RSC requires Masters degree projects to be ‘drawing on the chemical and related literature’. However, the direct comparability of QAA SBS makes them a useful tool for exploring disciplinary differences, hence their use in the current study. For an accurate picture of research literature use ‘on the ground’ further research is required, including first-person interviews with instructors and undergraduate students. While this would be of considerable interest, it is beyond the scope of the current study. However, the SBS based approach above provides the first systematic comparison of disciplinary literacies, and highlights that there is considerable variation in disciplinary norms that STEM educators working within a single discipline may have been unaware of.

The analysis above is not intended as a value judgement of particular subjects adopting the ‘right’ approach. Given the importance of prior knowledge in enabling (or disabling) comprehension, there is an argument that supports the teaching of core disciplinary content first, and then introducing research literature later on when students have built up appropriate schemas. However, this approach delays the point at which students encounter the authentic nature of communication within the discipline. It has been argued that ‘delay in exposing undergraduate science students to the real language and authentic processes of science can result in missed opportunities for undergraduate research experiences, and even the loss of science majors’ (Bruehl et al., 2015). For example, a first-year chemistry undergraduate may be asked to write a lab report without ever having seen a research paper, and may therefore struggle to understand the (seemingly arbitrary) disciplinary conventions being asked of their writing. Delay in encountering research literature may also reinforce a view of ‘science as facts’ that can be gained from a textbook (Phillips & Norris, 2009), rather than ‘science as process’ (Hoskins, Stevens, & Nehm, 2007).

Whatever the conventions of the discipline, it is important that students are first introduced to research literature in a gradual and supported way, rather than being ‘dropped in at the deep end’ without the skills and strategies to engage with disciplinary texts. The point at which this process starts may differ from subject-to-subject; for some disciplines (e.g. psychology) it might be at the very start of an undergraduate programme, for others (e.g. mathematics) it may be appropriate to delay this until postgraduate study. However this should be an active decision by course organisers and curricula should avoid sudden ‘leaps’ in requirements for using research-based literature.

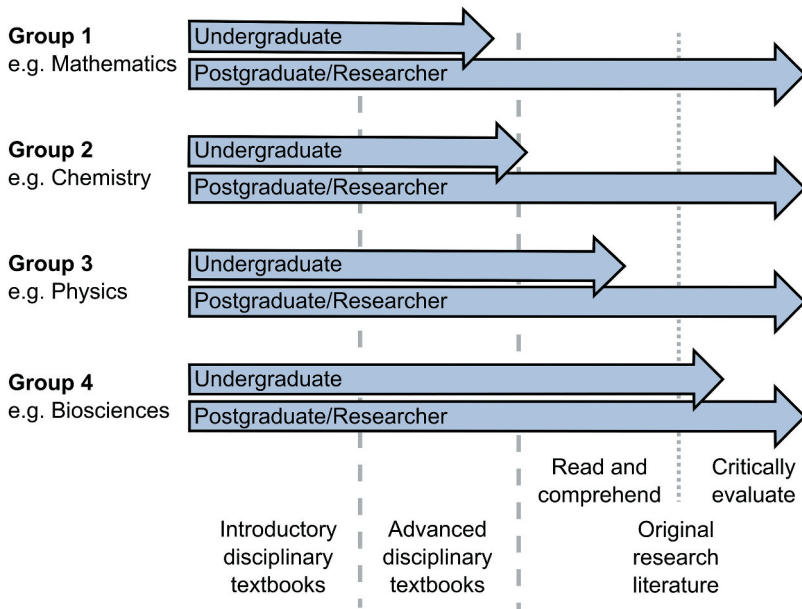


Figure 3. Results of the thematic analysis, illustrating disciplinary literacy requirements for UK STEM undergraduate degree programmes. All postgraduate researchers can be expected to engage with research literature in a critical manner, but there are disciplinary differences in the requirements for undergraduates to do so. Requirements were derived from QAA subject benchmark statements for the relevant disciplines; see [Table 1](#) for a full classification of subjects and references to benchmark statements.

Implications of disciplinary literacies for interdisciplinary STEM Education

There is an increasing focus on interdisciplinary STEM education, particularly through authentic problem-based learning (Daugherty & Carter, 2018). While there are many advantages to bringing students from different disciplines together, or exposing students to a broader range of disciplines, there are also challenges which include the disciplinary nature of literacy. Communication is seen as a key difficulty in establishing interdisciplinary research collaborations, with a lack of shared language contributing to frustrations within teams (Davé et al., 2016; Marchant & Gleed, 2016). This is also true for interdisciplinary STEM education. We all read from a disciplinary standpoint, so may struggle to engage with the requirements of a new discipline. Students working across disciplines are even less likely to have a coherent schema of knowledge than when they read within their subject area. This was demonstrated in a study of psychology and physics undergraduates, where students with prior misconceptions made more incorrect inferences from the text, and were less able to remember details of the source (Kendeou & van den Broek, 2007). Similarly, psychology students were less able to comprehend biological text than biology students, primarily due to a lack of relevant background knowledge (Ozuru, Dempsey, & McNamara, 2009). Simply encouraging students to read outside their primary discipline is therefore not enough; we need to ensure they have sufficient background knowledge before reading.

There are also challenges for academic staff when it comes to interdisciplinarity and literacy. It has been highlighted that peer review of interdisciplinary research papers is difficult, given the requirements of researchers to read outside of their own area of specialism, and the subsequent lack of coherent schema (Lee, 2006). This may have implications when preparing interdisciplinary course materials, and potentially leads to staff developing misconceptions about concepts in other disciplines. We may also have differing conventions or expectations between STEM subject areas, meaning students might be unsure what is expected when working across disciplines. If use of research literature is the norm in one subject area but not in others, do students and staff have a clear expectation of the level of literature use required? For example, it would be easy for me as a biologist to expect a level of research literature engagement from a second-year undergraduate that far exceeds what would be typical within chemistry. I might also assume a level of comprehension for my own discipline (e.g. understanding of statistical information presented in the text, which would be typical for biology), which would be unachievable to a student trained in another subject area. Clarity from course organisers here is key. Instructors need to be mindful of the differences in disciplinary literacies of their students, and how challenging it can be to read outside your primary discipline.

Effective teaching using research literature

What do we know about how students read complex disciplinary texts?

Given the centrality of reading and independent study in undergraduate education, there is a relative lack of literature on how undergraduate students actually engage with disciplinary texts. There are many studies (particularly within the biosciences) that address particular pedagogical approaches to teaching reading skills, and subsequent impacts on academic performance and student beliefs about science (e.g. Gottesman & Hoskins, 2013; Kozeracki et al., 2006; Lie et al., 2016; Stevens & Hoskins, 2014). There are also studies that focus on what students read, and how instructors can increase engagement with reading amongst their students (e.g. Hatteberg & Steffy, 2013; Hoeft, 2012; St Clair-Thompson et al., 2017). However, there are fewer studies that explore the processing and comprehension strategies actually used by students when reading challenging disciplinary texts and research papers. Shepherd, Selden, and Selden (2012) found that undergraduate maths students were not effective readers of textbook materials, being mostly unable to undertake a task based on material they had just read. Reasons for lack of reading effectiveness included displaying a lack of attention to the detail of the text, and having inadequate prior knowledge for comprehension (Shepherd et al., 2012). The most detailed study of undergraduates encountering research literature was performed by van Lacum, Ossevoort, Buikema, and Goedhart (2012), who found that students and researchers defined conclusions within a research paper differently, but that there was broad agreement between students and expert readers over which parts of the paper contained conclusions (van Lacum et al., 2012). A detailed study of two high-school students reading a research paper

indicated strategies used included connecting new information to prior knowledge, using diagrams, repeated reading, making predictions about the information contained within the text, and asking an expert reader for clarification (Brill, Falk, & Yarden, 2004). These inexperienced readers also ignored technical terminology they did not recognise (Brill et al., 2004). A questionnaire-based study of bioscience readers in a research-intensive university indicates that undergraduates engage with research papers differently to postgraduates and academics (Hubbard & Dunbar, 2017). Undergraduates found the methods and results sections of research papers particularly difficult to read, and that they valued the abstract and the discussion sections of papers most highly. This contrasts with researchers and academics who considered all aspects of papers easy to read, and valued the results and methods sections most highly (Hubbard & Dunbar, 2017). There is even less research that considers student reading strategies when crossing disciplinary boundaries and working in an interdisciplinary context. If we are to develop effective strategies for improving the reading abilities of students, we must pay more attention to the processes and strategies that they use when approaching complex text, and further research is needed in this area.

Approaches to developing scientific literacy

If we are to get students to engage with research literature in a meaningful way, we must use appropriate pedagogies to support the development of scientific literacy. While benchmark statements establish standards that should be met, such standards do not give an indication of what students need to learn to achieve these targets (Goldman et al., 2016). Viewing literacy from a disciplinary perspective helps us appreciate the need for STEM academics to teach STEM literacies. If we can recognise that the way we read is specific to our discipline, it naturally follows that disciplinary experts are the right people to teach subject-specific reading strategies (T. Shanahan & Shanahan, 2012). Equally, interdisciplinary researchers are the right people to teach interdisciplinary reading. Buehl (2017) calls on instructors to adopt a mentoring approach to disciplinary literacy, thereby allowing students to see the reading strategies used within the discipline.

‘Many of our students, even those who have achieved basic and intermediate literacy, do not develop independence in reading disciplinary texts, not because they are incapable but because they never received the appropriate instruction from appropriate mentors – disciplinary experts, the teachers who are accomplished readers, writers, and thinkers through their chosen disciplinary lenses’ (Buehl, 2017, p. 26).

We therefore need to develop teaching strategies that allow students to see how we read as experts, and structured opportunities to practice ‘expert’ reading skills within the discipline. If we are teaching across disciplines, we also need to give students the opportunity to model their reading on interdisciplinary experts. The key to this is appropriate scaffolding. Scaffolding can take many forms including self-guided question sheets, brainstorming, and interactive reading guides (Buehl, 2017). It is also important not to assume reading is a solitary activity; students who are struggling with complex text are unlikely to make breakthroughs in their reading without the opportunity to discuss the source and receive support (Buehl, 2017). We must also be mindful of students for whom English is not their first language, students with specific learning differences (e.g.

dyslexia), and those from educationally disadvantaged backgrounds whose literacy levels may not match those of their peers. To teach disciplinary literacy in an inclusive way, I strongly believe that this should be embedded within core curricula, and students given repeated opportunities to develop their processing skills before being expected to read independently. Reading needs to be accompanied by in-person discussion of texts, and openness about the challenges of reading complex materials.

Established pedagogies for developing research-led disciplinary literacy

While there are challenges for engaging students with any disciplinary text, there are unique challenges to introducing students to primary research literature. There are several guides online of ‘How to read a research paper’ (e.g. Rodriguez, 2015; Science Buddies, 2012; Thompson, n.d.; Williams, 2016), which may be beneficial to share with students encountering research papers for the first time. However, to fully engage students with research literature I call on STEM educators to embed literature-based teaching in their curricula, not just to send students away to read a paper accompanied by online guide. Many published strategies for incorporating primary research papers into taught curricula come from the biosciences (Hoskins et al., 2007; Kozeracki et al., 2006; Lie et al., 2016; Round & Campbell, 2013; Willmott et al., 2003), reflecting the centrality of literature use in these disciplines. However, approaches to incorporating research literature into undergraduate curricula have also been described for other disciplines (Bruehl et al., 2015; Carpenter & Pappenfus, 2009; Forest & Rayne, 2009; Locknar, Mitchell, Rankin, & Sadoway, 2012). Pedagogical strategies to developing disciplinary literacy can be applied across STEM disciplines (Stevens & Hoskins, 2014). I therefore present three published strategies for engaging students with research literature that may be of value in any STEM discipline. These may also be of value to interdisciplinary educators; as these strategies could be adapted when working across disciplines as well as within defined subject areas.

Example 1: Writing an abstract for a ‘classic’ paper

Willmott et al. (2003) describe an example of using literature within a first year (introductory) biochemistry skills module. In a taught session, undergraduates first brainstorm what sections of a scientific paper might contain, which are compiled in the correct order by the instructor to emphasise the structure of research articles. Students then consider three abstracts for a fictional paper to identify strengths and weaknesses. This highlights to students the importance of the title and abstract in encouraging researchers to read the full paper. In their own time, students then read a scientific paper and answer a series of structured questions about the material, and then write their own abstract for the paper. In subsequent sessions students write their own paper based on data provided by the instructor, and discuss this paper on a 1:1 basis with an academic tutor. Willmott et al. highlight that most contemporary research articles are very jargon heavy and inappropriate for use with students with limited technical knowledge. They therefore use a ‘classic’ paper which contains only a limited amount of data and a clear visual representation of the methodology (Macnab & Koshland, 1972), thereby reducing cognitive load (Willmott et al., 2003). This approach is therefore mindful

of the limited schema of knowledge that 1st year undergraduates have, and prioritises consideration of the structure of research papers rather than specialist knowledge contained within an individual study.

Example 2: Using key sentences to read research articles

Bennett and Taubman (2013) describe an two-stage approach used to encourage students to move from a 'literal' reading approach to a more 'inferential' and/or 'evaluative' reading style (Wilson & Chalmers Neubauer, 1988). This takes place in the context of a core 'Introduction to Chemical Research' module. In the first stage, students are provided with excerpts from either textbooks or journal articles, and are asked to identify 'key sentences' within the text, i.e. those sentences which articulate the main point of the paragraph. Students discuss whether the paragraph is clearly structured, and how the other sentences in the paragraph link to the key sentence. The second stage is an out-of-class formative assignment, which is based on identifying key sentences in the introductory section of a research article selected by the instructors. Working in groups, students are asked to create five Powerpoint slides based on the first five paragraphs of the paper, using the key sentence to organise their ideas. The slides must include definitions of key terms or explanations of key concepts, which requires students to link the information from the paper to other sources of knowledge. Students must also include one of the figures or tables from the paper in their slides, thereby requiring students to organise visual information as well as the text (Bennett & Taubman, 2013). Final assessment of the module is through a mid-term exam where students are asked a series of comprehension questions based on another published paper, and a group presentation. Introduction of the formative 'key sentences' assignment was associated with an increase in mid-term exam marks, although students saw the exercise as being more useful for preparing for the presentation (Bennett & Taubman, 2013). While this approach emphasises the introduction section of the paper rather than methods or results, it provides students with a practical strategy for approaching complex scientific text. It also highlights the need to triangulate reading of primary research literature with information from other sources, helping students to create a more coherent body of knowledge.

Example 3: C.R.E.A.T.E.

CREATE is a strategy designed to encourage undergraduate students to 'think like a scientist' through reading and analysing a series of papers from a single research lab over a number of taught sessions (Hoskins et al., 2007). For each paper, students are asked to Consider, Read, Elucidate the Hypotheses, Analyse and interpret data and Think of the next Experiment. During the 'Consider' phase, students define key terms in the article and create concept maps from the introduction section to ensure they have sufficient background knowledge. In the 'Read' phase, students read the results and methods sections in preparation for the class, drawing diagrams of each experiment, annotating the figures and writing their own descriptions of each figure. 'Elucidating Hypotheses' occurs during in class, where instructors support students into defining a specific hypothesis for each sub-figure within the paper. Students then 'Analyse and interpret the data' using

a template which asks them to relate the findings to the hypothesis, and to evaluate the quality of the data. The class then draws up a list of conclusions, which is compared to the discussion section of the paper. Finally, each student is asked to ‘Think of the next Experiment’, identifying the next experimental steps they would take. Crucially, this process is iterated for three more papers from the same research team, so that students can see the journey taken in the research process. Students also contacted the original research team and conducted a video interview with them, giving a personal insight into the research process they had followed through their reading (Hoskins et al., 2007).

CREATE is more than an approach to reading, but a strategy to engage students with the research process. It was originally developed for advanced classes in genetics, but has been adapted in a variety of subjects (Stevens & Hoskins, 2014), including in introductory classes (Gottesman & Hoskins, 2013). When pre- and post-class responses are compared, students taking CREATE classes score higher marks on critical thinking tests, report increased confidence in their reading abilities and have less stereotypical views of scientists (Hoskins, Lopatto, & Stevens, 2011; Hoskins et al., 2007). CREATE is suitable for students from diverse backgrounds and levels of education, and encourages students to see research science as a creative process (Stevens & Hoskins, 2014). It is a potentially powerful tool to engage students in scientific literature and the research process more generally. For resources, including examples of how CREATE has been used in Chemistry, Physics and Psychology, see <https://teachcreate.org/>.

Conclusions and reflections

Developing academic literacy is essential if students are to succeed academically. Within STEM this usually requires engagement with textbooks, but many disciplines also require undergraduates to engage with research-level materials. In other disciplines this may be delayed until postgraduate study, but at some point students will encounter research literature for the first time. We cannot assume that our students have the skills to be able to engage with disciplinary textbooks, let alone read and understand original research materials. We therefore need to embed disciplinary literacy development with the curriculum, and to give students strategies for engaging with complex disciplinary texts. I think the key to this is to share our reading experiences with our students, acting as reading mentors rather than expecting students to read independently. It is easy for us as academics to overlook how challenging we find reading scientific papers within our current specialisms, let alone remember our early encounters with the literature. I attend a weekly journal club in my department, and we often end up discussing how frustrating research papers can be to read, let alone comprehend! However, as academics we often do not share this experience with our students; we give them papers to read and imply that they should be able to read, understand and then write about the complex ideas contained within. In my own practice, I find it helpful to emphasise that research papers are the way that experts communicate with other experts, and that we do not expect undergraduates to understand every word of a paper. There are an array of pedagogical strategies that have been used

to help readers engage with disciplinary texts and research papers, and we should include these within taught programmes. We should also be mindful of the disciplinary nature of literacy if we are to develop effective interdisciplinary approaches to STEM education, as conventions of reading in different subject areas are not necessarily equivalent. Whether in a disciplinary or interdisciplinary context, we must embed inclusive strategies for developing academic literacy within taught curricula to enable all of our students to succeed. Finally, I call on STEM educators to teach academic reading with empathy, recognising that disciplinary texts can be extremely difficult to engage with. Being open and transparent about the challenges of learning to read in an academic context is critical if we are to effectively support students in their disciplinary literacy development.

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