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How do readers at different career stages approach reading a scientific research paper? A case study in the biological sciences

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ABSTRACT
Reading primary research literature is an essential skill for scientists. However, the high complexity of research papers may pose a barrier to the development of scientific literacy. In semi-structured interviews, we explore how 33 biologists including undergraduates, postgraduates and researchers approach reading an unfamiliar scientific paper. We find that some readers are data-centric, focusing on their own critical evaluation of the data presented, whereas others adopt a more narrative-centric approach, relying on the descriptions of authors to inform their understanding. There was a bias towards undergraduates adopting the narrative-centric approach and researchers adopting the data-centric approach. All postdoctoral researchers and academics prioritised critical interpretation of the data, indicating this is a characteristic of experienced scientific readers. The ability to demonstrate scientific reading skills was context-dependent, particularly with respect to time available and whether a paper aligns well with a reader's specialist area of knowledge. Inexperienced readers often lacked sufficient prior knowledge on which to base their reading, which represented a barrier to their engagement. We make recommendations for how scientific literacy should be developed within undergraduate teaching and beyond, noting that 'one-off' teaching strategies are insufficient when the development of scientific reading skills is a career-long process.

KEYWORDS
Scientific communication; scientific literacy; academic reading; disciplinary literacy; research papers

Introduction

The ability to read and interpret research literature is an essential skill for scientists and science students. Scientific writing is typically information dense, written in the abstract and uses complex terminology and sentence structure, so is challenging to engage with (Fang, 2005). There is a significant body of literature addressing the development of scientific literacy in a school context, where textbooks represent a linguistic challenge (e.g. Pearson et al., 2010; Snow et al., 2010). The challenges of developing scientific literacy continue into higher education, where learners must learn to read and interpret original research articles, which may be even less accessible than textbooks. In biology, undergraduates typically first encounter primary scientific literature early on during their degree (Willmott et al., 2003). In the UK, the Quality Assurance Agency (QAA) subject

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benchmark statement establishes that bioscience graduates are expected to have '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, 2015). This represents a very high expected level of scientific literacy in biology undergraduates (Hubbard, 2021). Undergraduate students are less confident when reading research papers than when reading textbooks (St Clair-Thompson et al., 2017). There is therefore a need to understand the challenges inexperienced readers face when reading scientific papers, and how someone becomes an 'expert' scientific reader. This study explores how readers at different career stages approach reading and evaluating a research paper.

The challenge of developing scientific literacy for bioscience undergraduates is reflected in the number of published articles describing approaches for literature-based teaching (e.g. Hoskins et al., 2007, 2011; Kozeracki et al., 2006; Willmott et al., 2003). Introduction of specific literature-based tasks can increase student confidence when reading research papers, and improve their critical analysis (Hoskins et al., 2011). Structured approaches to reading the literature can increase interest in and understanding of science (Hoskins et al., 2007), and increase retention of students into graduate study (Kozeracki et al., 2006). Similar interventions can help Masters students adopt higher order cognitive processing when reading, increasing their ability to critically evaluate research (Lie et al., 2016).

However, the majority of these pedagogical intervention papers make assumptions about how undergraduates approach reading. There have been fewer studies that focus on how scientific readers actually go about reading papers, either with or without appropriate pedagogically informed scaffolding. Van Lacum et al. (2012) identified that undergraduates are more likely to use linguistic and organisational features of the text, whereas experts typically use a content-driven approach. Undergraduates often struggled to comprehend technical terminology within papers, although some do attempt to evaluate research data (van Lacum et al., 2012). Nelms and Segura-Totten (2019) identified multiple strategies that expert readers used to reduce cognitive load while reading, and that inexperienced readers lacked relevant background knowledge when reading research papers. Brill et al. (2004) found that students read relatively superficially when first encountering a paper, but read more deeply when asked questions about the text, although this study included just two high school biology students. A study of how much undergraduates had engaged with a research paper before citing it suggests that most students engage with the introduction and results section (Verkade & Lim, 2016). We previously identified that biologists at different career stages valued different sections of research papers, with undergraduates more likely to prioritise the abstract and discussion, and experienced researchers more likely to value the figures, tables, results and methods sections (Hubbard & Dunbar, 2017).

Being able to read, understand and interpret scientific literature are characteristics of an 'expert' scientist. Experts are defined by having a large knowledge base of typical 'patterns' of knowledge in their discipline that they can quickly recognise, and can apply relevant disciplinary knowledge to unknown situations. In contrast, novices lack sufficient knowledge to be able to recognise disciplinary patterns, and have a limited capacity to apply appropriate knowledge (Perkins & Salomon, 1989). Many studies of scientific literacy development somewhat arbitrarily compare academics (faculty) as 'experts' with undergraduates as 'novices' (Nelms & Segura-Totten, 2019; van Lacum et al., 2012), without considering readers between these two career points. Our previous study suggested that the development of scientific literacy was an ongoing process throughout a scientific career, so that readers could not easily be classified into 'novice' and 'expert' readers as many studies assume (Hubbard & Dunbar, 2017). For example, our questionnaire indicated that there may be differences in reading strategy between PhD students, postdoctoral researchers and academics. We know less about how PhD students or postdoctoral researchers approach their reading and the relationship between scientific career stage and reading expertise. There is also an implicit assumption that scientific literacy training can be completed by the end of an undergraduate or masters level course, with all researchers and academics adopting 'expert' reading approaches (Lie et al., 2016).

In this study, we adopt a qualitative approach to understanding how biologists from undergraduates to academics (faculty) go about reading and critically evaluating a research paper. We present readers with an unfamiliar scientific paper, ask them to read it *in situ*, and ask a series of follow-up questions to understand their reading in more detail. Through this research design we ask the following specific research questions:

- How do scientific readers approach initial reading of an unfamiliar research paper?
- How do they critically evaluate information contained in an unfamiliar research paper?
- Does career stage or scientific reading experience influence either of these questions?

Methods

Interview design

Our previous methodology was questionnaire-based, asking scientists to give their general perceptions of reading. To explore what readers actually did when reading a research paper we adopted an interview-based methodology, whereby participants were presented with a paper, given time to read and answered questions about their reading. Other researchers have adopted similar 'think aloud' interview structures to understand of how readers engage with scientific texts (Nelms & Segura-Totten, 2019). We adopted a standardised open-ended interview format as this allows for depth of data collection while reducing interviewer bias (Cohen et al., 2017). Our research design captures 'initial' responses to reading an unfamiliar paper. We do not attempt to capture the detailed reading that might occur under other scenarios (e.g. Nelms & Segura-Totten, 2019; van Lacum et al., 2012). However, given the sheer volume of the literature both undergraduates and researchers are likely to 'skim read' many papers routinely, and many readers will skim read a paper first before re-reading in more detail. Our research design focusses on part of the reading process that may be overlooked if participants are asked to consider a paper over a prolonged period of time, or after they have been given scaffolded instructions on how to approach their reading.

Participants were recruited from those who had left contact details in our questionnaire study. These participants are drawn from a research-intensive, highly academically selective UK university, so may not be representative of all readers. Undergraduates in this university study their choice of three disciplines within Natural Sciences in their first (freshman) and second years, and then specialise in a sub-discipline of biological sciences in their third and final (senior) year. Interviews were conducted after end-of-year examinations, so undergraduates had completed all academic study for that year. Thirty-three interviews were conducted with nine second year undergraduates, seven final year undergraduates, five PhD students, six postdoctoral researchers and six academics (Table 1). Although this is a relatively modest sample, it is a larger sample size than other qualitative studies of scientific reading, and uniquely includes postgraduates and postdoctoral researchers. For example, Nelms and Segura-Totten (2019) interview 11 students and 6 faculty, while van Lacum et al. (2012) only interview four undergraduates.

Interviewing was split between four interviewers who worked from a script to maximise consistency, although interviewers made minor changes to wording or ordering of questions in response to the flow of conversation. After asking demographic questions, participants were asked to indicate their preference from four sub-disciplines of biology, and then presented with a paper copy of a research study in that area (Biochemistry: Shroff et al. (2015); Ecology: Galbraith et al. (2015); Physiology: Ranade et al. (2014); Plant Sciences: Benedetti et al. (2015)). Papers were pre-selected on the basis of all being from the same journal (Proceedings of the National Academy of Sciences USA), being published within a 2 year window, and including an assertive statement in the title. The most commonly chosen sub-discipline was Ecology ($n = 12$), followed by Biochemistry ($n = 11$), Physiology ($n = 7$) and Plant Sciences ($n = 3$; Table 1). We gave participants a few minutes to familiarise themselves with the paper but did not set a time limit, so participants were free to restart the

Table 1. Career stage, paper chosen, time spent reading and reading pattern of each participant.

Name	Career Stage	Article	Familiarity	Time Spent Reading (minutes)	Reading Pattern
Aaron	Undergraduate (2nd Year)	Physiology	C – Know the basics	2.35	Narrative
Danielle	Undergraduate (2nd Year)	Physiology	C – Know the basics	3.13	Narrative
Emily	Undergraduate (2nd Year)	Ecology	C – Know the basics	3.88	Narrative
Felix	Undergraduate (2nd Year)	Ecology	C – Know the basics	7.03	Holistic
Hannah	Undergraduate (2nd Year)	Biochemistry	C – Know the basics	8.15	Narrative
Isobel	Undergraduate (2nd Year)	Biochemistry	B – Quite familiar	16.70	Holistic
Michelle	Undergraduate (2nd Year)	Physiology	C – Know the basics	14.98	Holistic
Owen	Undergraduate (2nd Year)	Ecology	B – Quite familiar	1.27	Data
Rachel	Undergraduate (2nd Year)	Biochemistry	C – Know the basics	13.15	Holistic
Ben	Undergraduate (3rd Year)	Physiology	C – Know the basics	3.42	Narrative
Chris	Undergraduate (3rd Year)	Biochemistry	B – Quite familiar	3.23	Narrative
Graham	Undergraduate (3rd Year)	Ecology	D – Unfamiliar	4.05	Data
Jemima	Undergraduate (3rd Year)	Ecology	B – Quite familiar	2.67	Narrative
Katy	Undergraduate (3rd Year)	Plant Sciences	C – Know the basics	2.30	Narrative
Natalie	Undergraduate (3rd Year)	Ecology	C – Know the basics	1.92	Abstract Only
Phoebe	Undergraduate (3rd Year)	Ecology	D – Unfamiliar	8.63	Narrative
Euan	PhD student	Ecology	C – Know the basics	6.42	Narrative
Gabriella	PhD student	Biochemistry	B – Quite familiar	2.67	Holistic
Simon	PhD student	Biochemistry	D – Unfamiliar	4.05	Data
Tracy	PhD student	Ecology	C – Know the basics	4.72	Data
Victor	PhD student	Biochemistry	B – Quite familiar	5.03	Data
Amy	PostDoc	Biochemistry	C – Know the basics	1.52	Data
Frances	PostDoc	Ecology	B – Quite familiar	6.80	Data
Henry	PostDoc	Biochemistry	C – Know the basics	2.33	Data
Laura	PostDoc	Biochemistry	D – Unfamiliar	5.63	Data
William	PostDoc	Ecology	B – Quite familiar	3.33	Data
Zach	PostDoc	Plant Sciences	C – Know the basics	3.05	Data
Barbara	Academic	Plant Sciences	A – Very familiar	1.30	Abstract Only
Chloe	Academic	Biochemistry	C – Know the basics	3.70	Data
David	Academic	Physiology	C – Know the basics	5.42	Data
Liam	Academic	Physiology	B – Quite familiar	3.27	Data
Robert	Academic	Ecology	C – Know the basics	1.07	Abstract Only
Yvonne	Academic	Biochemistry	D – Unfamiliar	1.58	Data

interview when they felt ready. Participants were asked to indicate where in the paper they were reading as they went along to allow the interviewer to observe their reading, and observations were cross-checked with subsequent descriptions. Having read the paper, participants were then asked how familiar they were with the topic area from a series of four statements (A – I am very familiar with the topic; B – I am quite familiar with the topic; C – I know the basic ideas, but not much detailed information; D – I am unfamiliar with the topic). The interview then progressed with the following prompt questions:

Q8 Which sections did you look at while you were familiarising yourself with the paper?
Q9 What did the paper show?
Q10 Do you think the authors have proved the claim they make in the title?
Q11 What did you look for in deciding how convincing the paper was?
Q12 This paper has been peer reviewed. What do you understand by that?

Participants had access to the paper for the remainder of the discussion and many referred back to the paper during the interview.

Data analysis

After all interviews were completed, the four interviewers met to discuss their initial impressions, and identified potential areas of interest for more formal analysis. Interviews were then manually transcribed and redacted for identifying information, or information that revealed interviewee career stage. For six transcripts, career stage redaction was not possible, as the substantive content of the interview responses revealed that they were either a researcher or an undergraduate.

After redaction, two members of the research team performed thematic analysis of the transcripts. Thematic analysis is a method for determining patterns within a dataset, so is a flexible qualitative research methodology that does not rely upon a particular theoretical perspective (Braun & Clarke, 2006). Braun and Clarke (2006) highlight that thematic analysis should acknowledge the role of the researcher, using the active terminology 'we developed themes from the data' rather than the passive language of 'themes emerged'. We therefore use the former language to reflect on our active development of themes as researchers. We broadly followed Braun and Clarke's six-stage process for analysis. Both Braun and Clarke and Nowell et al. (2017) suggest that initial themes should be derived from the dataset itself. The first 'familiarisation' phase included the initial interviewer discussions, the transcription process and iterative reading and re-reading of each of the transcripts. In the second 'initial coding' stage, both researchers independently coded all transcripts, generating a list of preliminary codes and groupings. Both researchers independently carried out the third 'searching for themes' phase, with both identifying four putative key themes. The fourth and fifth phases of 'reviewing themes' and 'defining and naming themes' happened through a series of collaborative discussions. After discussion and review, we agreed upon 'key' themes, including sub-themes where appropriate. 'Evaluation Strategy' was the focus of one of our research questions, so was constructed deductively. 'Prior Knowledge' and 'Reading Context' were constructed inductively from the initial codes. The themed coding scheme was then passed to a researcher who had not been an interviewer, who independently coded all transcripts in NVivo12. There was 95.7% percentage agreement between the two sets of coding, with a Cohen's Kappa value of 0.64, indicating a good level of agreement (Dawson & Trapp, 2004). The final writing stage was conducted by a single member of the research team. During the writing process participants were given a gender-matched pseudonym for easier tracking of individuals through the manuscript.

We separately analysed the answers to Q8 'Which sections did you look at while you were familiarising yourself with the paper?' to explore the reading 'patterns' described. Transcripts were converted to reading pattern diagrams (see Figure 1), whereby descriptions were mapped against the structure of a research paper, including the order in which sections were described. This also took note of qualifying statements such as '*I skipped over … .*' '*I didn't understand …* '. These diagrams were then iteratively sorted into groups of similar patterns, generating three final pattern classes. Initial classification was performed by one researcher while career stage was still redacted, and then confirmed by an independent researcher, with an inter-rater reliability of 93% (28 out of 30). The 'Abstract only' readers were removed from this analysis as their reading pattern could not be determined.

Ethical oversight

The study was designed in line with British Educational Research Association (BERA) ethical guidelines (BERA, 2011). All participants were provided with a study information sheet, which described the purpose of the study, anonymisation procedures, how their data would be used and opportunities for withdrawing from the study. All participants had the opportunity to ask questions about the conduct of the interview, and gave written and verbal consent for participation. At the time of the interviews there was no formal ethical approval process, but permission to conduct the research was given by the Departmental Director of Learning and Teaching. Oversight for analysis is provided by the University of Hull Faculty of Science and Engineering Ethics Committee (project code FEC_2019_10).

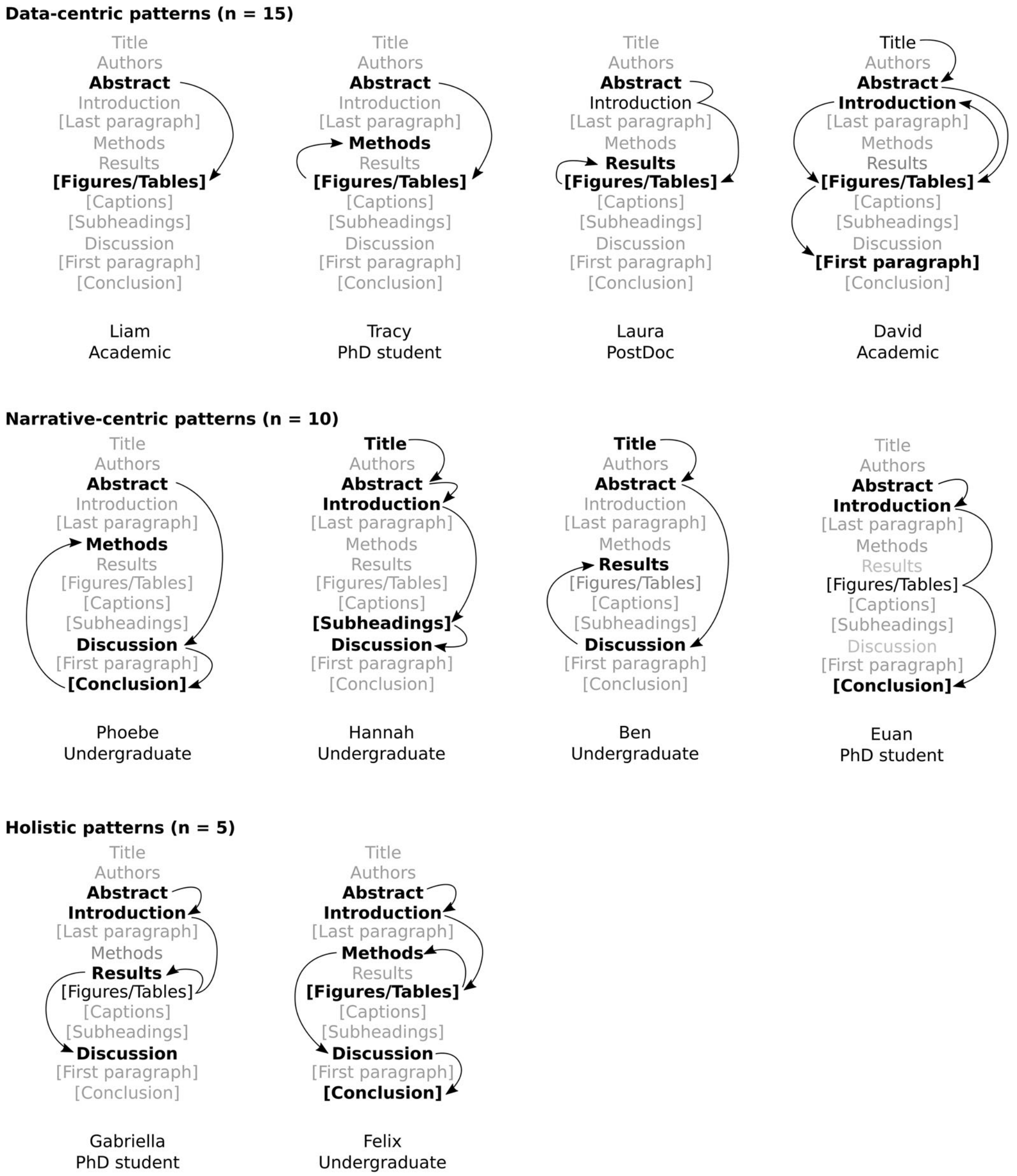

Figure 1. Example reading patterns. Sections in square brackets are subsections of the paper. Sections highlighted in black text were specifically mentioned by participants. Sections that participants described with statements such as 'I skipped over … .' are presented in unbolded text and with a 'bounce' arrow without an arrowhead.

Results

Each participant was presented with a paper relevant to their chosen sub-discipline. After reading the paper participants were asked which of four statements best described their level of familiarity with the topic. The most common response was 'I know the basic ideas, but not much detailed information' ($n = 19$), followed by 'I am quite familiar with the topic' ($n = 8$) and 'I am unfamiliar with the topic' ($n = 5$). Only one participant said they were very familiar with their topic. We quantified the length of time participants spent reading from the recordings, ranging from 1 min 10 s to 16 min 42 s. There was no significant difference in reading time between researchers and undergraduates (Kruskal–Wallis H = 1.09, $P = 0.30$), as a function of interviewer (H = 1.29, $P = 0.73$), article chosen (H = 3.38, $P = 0.34$) or self-reported familiarity with the topic (H = 2.64, $P = 0.45$). This indicated that the interviews were broadly equivalent.

Experienced readers tended to be data-centric

We first asked participants which sections of the paper they looked at. The most commonly mentioned sections were the abstract ($n = 30$), followed by the results ($n = 28$) and the discussion ($n = 20$). Only nine participants mentioned looking at the methods section. However, this quantification underrepresents the complexity of narrative many participants gave when describing their reading, so we adopted a qualitative approach. We analysed the descriptions of which (sub)sections of the paper participants read, and the order in which they read them (Figure 1).

From these descriptions, we identified three reading patterns we termed 'data-centric' ($n = 15$), 'narrative-centric' ($n = 10$) and 'holistic' ($n = 5$). Readers who only looked at the abstract are excluded. Data-centric readers typically described looking at the figures, graphs or data rather than the results in general. They often stated that they did not use the text, but preferred to interpret the data for themselves (e.g. Tracy, PhD student).

> I read the abstract because that gave me an overview of what they were doing. I then just looked at the figures because I can understand them much more quickly than reading the text. And then I just flicked through to the methods to clarify what their experimental treatment was. – Tracy, PhD student

Data-centric readers tended to skip over the introduction, methods and discussion sections, instead going straight to the figures (Figure 1). Some data-centric readers went to the figures first, then went back to the introduction for additional context, then returned to the figures to assess the data directly (e.g. David, academic).

In contrast, narrative-centric readers preferred to rely on the author's description of their findings. Some narrative-centric readers did not use the figures and tables at all, relying on the text instead (e.g. Ben, undergraduate). Others attempted to engage with the figures but struggled, so moved to sections where the authors had described their findings in words (e.g. Phoebe, undergraduate). Narrative-centric readers sometimes referred to visual aids as 'pictures' or 'diagrams' rather than graphs or figures. However, this was not a classification criterion as it may have reflected inexperience in scientific terminology rather than the reading pattern used.

> I read the abstract first all the way through to try get an idea of what it was about - I read the title and then I read the abstract. Then went and had a look at the discussion and read that all the way through - it usually gives quite a good idea I find to get the methods they used and what the key results were. And then I went and looked at the opening few lines of each of the results section – Ben, 3rd year undergraduate

> I just read the abstract briefly to get an idea of what it's about, then I felt I should move onto the discussion. It was quite a long discussion so that put me off a little bit - I don't think I took in as much as I could have by reading the discussion. Then I finished with the conclusion and checked over the methods to see what they actually did. But the statistics confused me so I skipped over that. – Phoebe, 3rd year undergraduate

Some readers could not be easily classified as either data- or narrative-centric, as they described using the figures and tables as well as the text, so we classified these as 'Holistic' readers (e.g. Gabriella, PhD student). Holistic readers took longer to read the paper (mean = 10.9 min) than either the data-centric (3.7 min) or narrative-centric readers (4.4 min) but this difference was not significant (Kruskal–Wallis H = 5.55, $P = 0.063$).

> I read the abstract, I had a quick look at the figures just so I had a rough idea what was going on, then I read the results, and then went through the discussion. – Gabriella, PhD student

We were interested to see if there was a relationship between reading pattern and familiarity with the topic or career stage. While our sample size is too small for formal statistical analysis across the five career stages, there were some biases in categorisation. There was no obvious relationship between the reading pattern adopted and self-reported familiarity with the topic (Figure 2(A)). However, there was a tentative relationship between career stage and reading pattern (Figure 2 (B)). Within the undergraduate and PhD students there were narrative-centric, data-centric and holistic readers, but all academics and postdoctoral researchers were data-centric. There was no obvious relationship between self-reported familiarity and career stage (Figure 2(C)), indicating that the career stage pattern could not be explained by familiarity with the topic chosen.

Readers use a variety of strategies to critically evaluate papers

We asked participants a series of questions about the paper, including how they assessed whether the authors had proved the claim made in the title. From these responses we developed 'evaluation strategy' as a key theme, with three subthemes (Table 2). The first subtheme was 'experimental information', where participants looked for information within the paper to assess the reliability of the data ($n = 30$). The second subtheme 'Written arguments' related to the way the authors had written the paper, and how persuasive the writing was ($n = 16$). The 'External' subtheme included participants wanting to find out information that was not contained within the manuscript ($n = 11$), or proxies for reliability such as the journal.

Within 'evaluation strategy' there were two types of description. Some participants discussed what they had actually done to review the paper within the interview, whereas others described what they would do to critically evaluate research papers more generally. For example, Liam (academic) described specific information from the figures and methods he used to make judgements in real time. In contrast, Hannah (undergraduate) described what she would have done given more time, indicating she knew what should be done to evaluate reliability, but had not done so in this setting.

> On Figure 3 there seems to be a substantial disparity between the experimental groups in the histogram in Figure 3D. The level of significance in Figure 3B is only 0.05 so that's only a relatively weak effect. – Liam, Academic

> [Given more time] I would definitely read the results. Their experimental techniques and how they'd drawn their conclusions. What have you done? What question are you asking with this? That's the kind of thing I would look for. – Hannah, 2nd year undergraduate

Other participants were much less sure about how to evaluate the paper, or indicated that they would rely on external proxies for reliability such as the journal (e.g. Gabriella, PhD student).

Table 2. 'Evaluation strategy' theme summary. N_{people} indicates the number of participants who mentioned this subtheme, $n_{mentions}$ indicates the total number of times this subtheme was mentioned.

Subtheme and Specific codes	$n_{mentions}$	n_{people}	Illustrative quotes
Subtheme: Experimental information	**77**	**30**	
- Controls & Replicates	27	19	*I'd look for the controls that they used in their experiments to see if they were sound.*
- Statistics & data	22	18	*n is 188 - I doubt that's 188 mice.*
- Experimental design	24	15	*Is it a correlation or an active manipulation?*
- Clear effect	4	4	*In Figure 3 there seems to be a substantial disparity between the experimental groups.*
Subtheme: Written arguments	**32**	**16**	
- Data match description	11	10	*What I did do was look at the graphs versus what they were saying in the discussion.*
- Strength of Claim vs level of proof	10	7	*I don't know if the amount of certainty in the title is portrayed in the degree of their results*
- Logic of argument	4	4	*Have all of the majorly important questions been addressed to draw the conclusion the authors draw?*
Subtheme: External information	**15**	**11**	
- Compare to other papers	8	7	*If one paper says something I tend to want to look for other authors in the same field agreeing with them.*
- Authors/ journal/other	6	3	*The journal does have an influence on this judgement - PNAS is a good journal.*

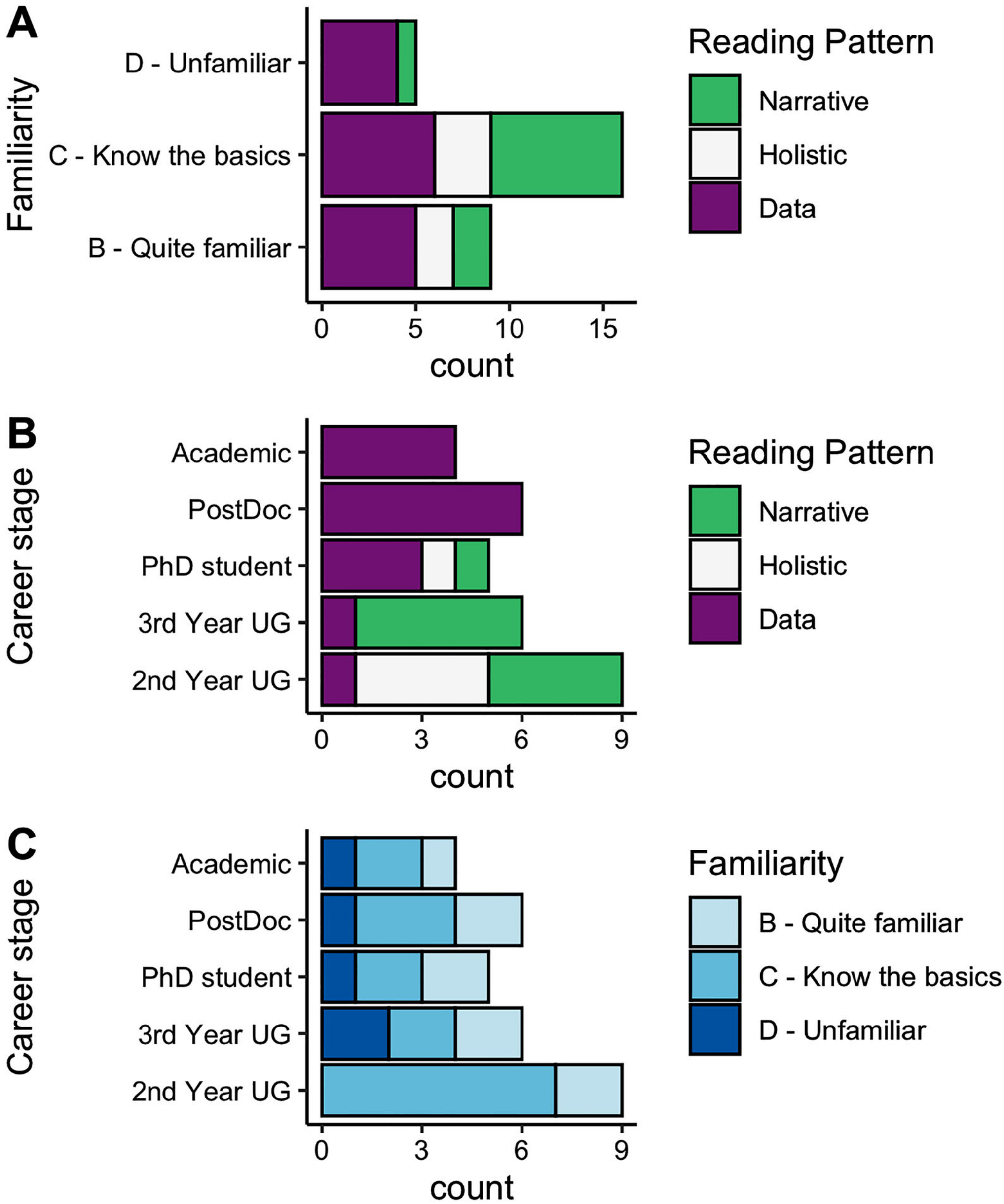

Figure 2. Summary of Reading Patterns by (A) self-reported familiarity with the topic and (B) career stage. (C) presents the self-reported familiarity with the topic by career stage for reference. The 'Abstract Only' readers are not included as their reading pattern could not be determined.

> What sort of controls they have used, whether they have any conflicts of interest with the people who have produced it – the research place they came from, Stamford. It seems quite above board. PNAS has a good review. – Gabriella, PhD student

Participants who described a relatively superficial approach to critical evaluation tended to be undergraduates or PhD students. However, several undergraduates and most PhD students had some understanding of how to evaluate data, so it would be incorrect to assume that all inexperienced readers were unable to critically evaluate the paper.

Prior knowledge and context inform reading approach

In reviewing the descriptions of reading pattern and critical evaluation, we noted several mentions of how reading approach might have differed in a different situation (e.g. Hannah above). We also observed that several participants mentioned their (lack of) prior knowledge. We therefore developed 'Prior Knowledge' and 'Reading Context' as themes (Table 3).

The most frequently mentioned 'Prior Knowledge' subtheme was lack of expertise as a barrier ($n = 9$), followed by how their reading strategy might have differed if they were more familiar with the specific research area ($n = 5$). Many undergraduates described a general lack of knowledge (e.g. Rachel, undergraduate) or struggled to say what the paper showed (e.g. Phoebe, undergraduate). However, other participants described lack of knowledge in reference to the specific topic of the research paper, despite being (highly) experienced in reading the literature in general. This was most explicitly described by Yvonne, a senior academic who chose the biochemistry paper. However, her expertise was in a completely different study system, biochemical pathways and experimental methods, so she reported 'D – I am unfamiliar with this topic'.

> I don't think I have adequate knowledge in any subject to thoroughly critically review papers. So I trust them somewhat, but I don't have the knowledge to properly critique them, or the time to read all of the papers behind it. – Rachel, 2nd year undergraduate

> I'm not sure where to begin. I feel like they were trying to show experimentally which they'd only shown by correlations before. But I'm not sure that they were that successful. – Phoebe, 3rd year undergraduate

> Well if I knew about any of the techniques I would be looking at the techniques, but I don't know anything about them. They've done in situ [hybridisation]; I think that's the brown blobs there showing its being expressed, so that's pretty looks pretty convincing. – Yvonne, Academic

While both of these participants described lack of prior knowledge as a barrier to critical evaluation, their lack of knowledge was at a very different level. Rachel and Phoebe describe a general lack of scientific knowledge, whereas Yvonne describes a lack of specific sub-disciplinary knowledge that came from reading outside her field of expertise.

The most commonly mentioned 'Reading Context' subtheme was the time available in the interview for the reading task ($n = 10$), followed by the purpose of reading ($n = 8$). Graham and Owen (both undergraduates) typify these two subthemes.

> Because it was a short period of time I didn't look at the introduction, but I would usually read that first. Had I been reading it under un-timed conditions it would have been Abstract, Introduction, Discussion, Results then scan the materials if it was interesting. – Graham, 3rd year undergraduate

> I think if the paper was then something that I was particularly interested in then I'd go on to read the discussion. And if I was going to critique the paper, or I was looking to do a similar experiment myself, I'd look deeper into the methods. Owen, 2nd year undergraduate

Table 3. 'Reading Context' and 'Prior Knowledge' theme summaries.

Prior Knowledge Subthemes	$n_{mentions}$	n_{people}	Illustrative Quote
- Lack of Expertise as a barrier	11	9	*In this particular case I definitely need to know more about the glycolysis and glutamine pathway.*
- Level of knowledge affects strategy	10	5	*First I read the title and abstract, then intro just because I don't really know much about the topic.*
- General scientific knowledge	3	3	*From my own purely amateur experience in this field I'm not surprised by the findings they give in the abstract.*
Context Subthemes	$n_{mentions}$	n_{people}	Illustrative Quote
Time	11	10	*Because it was a short period of time I didn't look at the introduction, but I would usually read that first.*
Purpose of reading	10	8	*If I was sure this paper was going to be useful, so someone has suggested it to me, I would probably just read it all the way through.*
Own research	2	2	*If it's closer to anything that concerns my direct research I might go straight into … the methods or figures*

In addition, two researchers described the relationship between their direct area of research and the paper they were reading (Table 3).

Discussion

In this study, we explored what biologists from a range of career stages did when presented with a novel research paper and how they went about critically evaluating it. Participants prioritised different sections of the paper, and differed in the order in which they read it, and the information they extracted. A major difference in reading approach was whether individuals read in a 'data-centric' way, choosing to interpret figures/tables directly without prompting, or whether they read in a 'narrative-centric' way relying on authors descriptions of their findings. We found that undergraduates were more likely to be 'narrative-centric', while researchers were mostly 'data-centric' readers, but variation between individuals meant that reading pattern could not be inferred from career stage. We identified multiple strategies that readers used to evaluate the quality of a research paper, and that prior knowledge and reading context influence engagement with a research paper.

What does it mean to be an experienced scientific reader?

All of our academics and postdoctoral researchers adopted a data-centric approach to reading, suggesting this is a characteristic of experienced readers. They adopted a critically evaluative reading approach without being prompted to do so. In contrast, many of our inexperienced undergraduate readers and some postgraduates relied on the narrative of the paper for their understanding, and often found their lack of knowledge to be barrier to deeper engagement with the paper. This suggests that reading experience is multi-faceted, including development of prior knowledge, and adopting strategies to prioritise reading and criticality. A link between lack of reading experience and surface-level reading strategies is well documented (Alexander, 2003, 2005; Brill et al., 2004; Hoskins et al., 2011; Lie et al., 2016), therefore our findings are broadly consistent with other studies of scientific literacy development. They also potentially align with broader research on the nature of disciplinary expertise, whereby our 'data-centric' mode of reading may represent a characteristic reasoning pattern typical of experts (Perkins & Salomon, 1989).

To understand new information we need to be able to relate it to existing knowledge (Harrison & Perry, 2004; O'Donnell & Wood, 2004). Schema theory proposes that readers organise their knowledge into networks of inter-related concepts, that are iteratively built on with each new piece of information (Anderson & Pearson, 1984). For example, a biochemist might have a schema of knowledge about a particular metabolic pathway and techniques used in the field. The biochemist can link new information (e.g. new findings about an enzyme) to their existing schema of knowledge, therefore comprehending it. An ecologist lacks this schema, so is less able to comprehend the new information, and less likely to retain it. The importance of a coherent schema of knowledge was demonstrated by our participants. Liam (academic) clearly had detailed prior knowledge about the topic of his paper even though it was not his immediate area of expertise, so was immediately able to make connections between his existing understanding and the new information in the paper. In contrast, Phoebe (undergraduate) found her lack of knowledge to be a barrier to engaging in the paper, and could only make relatively superficial statements about it. Nelms and Segura-Totten (2019) also found that novice readers lacked the complex schema of knowledge that expert readers relied on when reading a paper.

Yvonne demonstrates how specialised a coherent schema of knowledge needs to be. Although her expertise was in biochemistry, the paper we gave her described an unfamiliar pathway, model species and experimental techniques. As such, she had a fragmented mental model to base her reading on. Alexander (2003) separates knowledge into 'domain' and 'topic' knowledge. 'Domain' knowledge represents the broad understanding of a subject area e.g. general scientific principles. In contrast, 'topic' knowledge concerns depth of knowledge in specific areas, e.g. how a particular gene is regulated (Alexander, 2005). Yvonne exemplifies someone with high domain knowledge, but limited topic knowledge. However, Yvonne's lack of topic knowledge did not stop her adopting a critically evaluative, data-centric reading pattern. This suggests reading patterns of experienced readers are more associated with domain knowledge than topic knowledge.

A key characteristic of our data-centric readers was focussing on the information presented within figures and tables rather than the text itself. This presents an interesting paradox, whereby learning to 'read' scientifically is partially characterised by prioritising visual information over written words. This observation is supported by several other studies of expert readers (Bowen et al., 1999; Harsh et al., 2019; Nelms & Segura-Totten, 2019; Shanahan et al., 2011; Weinberg et al., 2016). Scientific texts are unusually rich in inscriptions (graphs, diagrams, tables, formulae etc), which are central to understanding the document (Bowen et al., 1999; Bowen & Roth, 2002). Being an experienced scientific 'reader' is more than being able comprehend text, but also requires skills including visual and statistical interpretation. Some of our inexperienced readers did not use the figures at all, even when prompted to critically evaluate the paper in later questions. Others attempted to engage with the figures but found themselves unable to interpret the information, so turned instead to textual descriptions they found easier to engage with (e.g. Phoebe). Others have highlighted how challenging interpreting inscriptions can be for undergraduates, and that these skills need developing in their own right (Bowen et al., 1999; Harsh et al., 2019). Our study was not designed to explore how readers approached graphical interpretation, but this warrants further attention, particularly where readers changed their reading strategy when they are unable to interpret inscriptions.

While we find clear evidence for 'data-centric' and 'narrative-centric' reading patterns within our study, our 'holistic' category may not be as well supported by additional research. It might be that our holistic readers genuinely combined a narrative-centric and data-centric approach, or it might be that the constraints of the interview situation resulted in them reading the paper in a way that might not reflect their reading in a different setting. It should be noted that our holistic readers took longer to read the paper than either data-centric or narrative-centric readers, so might have interpreted the task differently, or may have felt uncomfortable re-starting the interviews before reading the whole paper. Other studies asking students to reflect on their reading have found that undergraduate readers do engage with multiple sections of a research paper, and a majority attempt to understand how the results support the conclusions (Verkade & Lim, 2016). This could support the existence of a holistic mode of reading, or might indicate that most readers adopt more data-centric approaches given more time. As there were only five holistic readers in our sample population and there are multiple reasons that might account for this reading pattern, the establishment of this category should not be over-interpreted. Considering scientific reading patterns in more authentic settings with a larger sample size may help to establish whether 'holistic' is a genuine categorisation of reading behaviour.

Comparison to conceptual frameworks

Given the complexity of what it means to be an experienced reader, it is likely that developing scientific reading skills occurs gradually over an extended period of time. The most relevant model that presents learning to read as a life-long process is Patricia Alexander's Model of Domain Learning (MDL) (Alexander, 1997, 2003, 2005). Readers start from an acclimation state, then move through competency to proficiency/expertise. During acclimation, readers encounter unfamiliar terminology and conventions, have fragmented understanding of the subject, and are poorly able to distinguish between relevant and irrelevant information. They therefore adopt surface-level reading strategies. As readers gain a more coherent understanding within their discipline they enter competency, adopting deeper processing strategies such as questioning the source. Proficient readers have broad and deep understanding of their discipline, adopt deep-processing strategies and typically actively contribute to their field by creating new knowledge. Expert readers have deeper knowledge still, and seek transformative new ideas through their reading (Alexander, 1997, 2003, 2005). Acclimating readers typically have situational interest in the source (e.g. reading for an assignment), whereas proficient/expert readers generally read for personal or professional interest (Alexander, 2005).

Although our study was not designed to formally align with the MDL, we have tentative evidence for readers in the acclimation, competent and proficient/expert phases. Phoebe and Graham (both undergraduates) are probably acclimating readers who adopted surface-level approaches and lacked prior knowledge required for deeper engagement. Tracy (PhD student) might be a competent reader as she had a clearer strategy for reading, and demonstrated some deeper level processing. Liam (academic) demonstrated the knowledge and deep-processing abilities typical of proficient or expert readers. However, other participants would not easily be classified on Alexander's model. Is Yvonne (academic) a proficient reader, or is she only competent in this scenario due to her limited topic knowledge? Is Hannah (undergraduate) a competent reader because she knows what she should do when reading, even if she actually read more like an acclimating reader? Given the importance of reading context, it is unlikely that a reader could be accurately classified on the MDL through research designs involving a single text. However, the similarities between our analysis and the MDL make it a valuable framework for alignment of future research.

An alternative conceptual framework that be relevant is that of 'reading thresholds', which draws on the threshold concept literature to establish that there are particular aspects of learning to read that once learned cannot easily be unlearned (Abbott, 2013). This model sees development of reading expertise as a series of unidirectional steps, rather than the gradual transitions proposed in the MDL (Alexander, 2005). For example, Davies (2018) proposes that seeing scientific papers as persuasive documents rather than descriptions of objective scientific facts is a reading threshold. While this study did not aim to explore thresholds, it is possible that this model explains the difference between our narrative- and data-centric readers. The narrative readers may not have passed through this threshold so were happy to rely on the author descriptions, not realising that these are subjective. The data-centric readers may have passed this threshold, so preferred to critically evaluate the data for themselves. There is some evidence within our data to support this idea. Yvonne read in a data-centric way typical of having passed through the threshold, even when reading in a discipline she was unfamiliar with. This threshold model would also account for the fact that there was variation in reading approaches amongst our early career readers, but all our post-doctoral and academic readers read in a similar data-centric way implying all had passed the threshold. Further research into our narrative- and data-centric classifications should aim to explore (i) whether narrative-centric readers can become data-centric readers (ii) whether this transition is gradual or abrupt and (iii) whether there are specific reading thresholds that define differences between these reading styles. This may help to define what constitutes 'expert' scientific reading, and what factors influence whether an individual has become an expert reader.

Limitations of data and future directions

While our findings are broadly consistent with others, there are limitations of our research design that need to be considered. Our study was designed to capture initial impressions of a scientific paper within the interview situation, so may not reflect how participants might have engaged with the text in their own time. To gain a more accurate understanding of how readers approach scientific papers it would be of value to conduct similar studies in a more realistic setting(s). Our research design also does not allow us to explore how an individual may change their reading strategy depending on the context. We also only consider reading within the biosciences, a discipline that requires relatively early and deep engagement with the literature (Hubbard, 2021). In other disciplines, our findings may be more relevant to postgraduate education. Our participants are entirely drawn from one institution with very high academic entry standards, so our undergraduates are likely to have higher than average reading abilities. It is likely that the challenges our readers had will be even greater for those reading in a second language, those with dyslexia and those with lower overall literacy levels. It would be of interest to extend investigations of scientific reading to other institutions with different student demographics, and across disciplines. It should also be noted that our design relies on sampling strategy to infer how reading may develop across a scientific career, but a longitudinal research design is required to fully answer this question.

Our study provides evidence that scientific reading approaches change as readers gain experience and expertise in engaging with the literature. However, the modest size of our sample and research design do not currently allow us to clearly separate experience and expertise from career stage. While we can reasonably assume that academics (faculty) are experienced scientific readers, similar assumptions cannot be made for other career stages. This is particularly relevant for postgraduates; some of our PhD students adopted data-centric reading patterns typical of experienced readers (e.g. Tracy), others took a more narrative-centric or holistic approach to reading (e.g. Gabriella and Euan). While some undergraduates took a relatively naïve or superficial approach to reading the paper, others adopted a more data-driven critical approach. We therefore cannot infer 'novice' or 'expert' reading behaviours simply from career stage. Our previous research also found differences between undergraduates, PhD students, researchers and academics in terms of how easy they found the results section to engage with (Hubbard & Dunbar, 2017), suggesting that binary classifications of 'expert' and 'novice' readers by career stage are overly simplistic. Much of the literature in this area compares undergraduates with faculty (Nelms & Segura-Totten, 2019; van Lacum et al., 2012; Weinberg et al., 2016), so does not allow the gradual journey towards expertise to be considered. Given that models such as the MDL emphasise that building expertise takes a long time (Alexander, 2003), more detailed studies involving Masters students, PhD researchers and postdoctoral researchers are required. It would also be useful to collect information on how many papers participants read per week, and an estimate of the total number of papers the individual had ever read (although this may be difficult to capture accurately). Further research with a larger sample size is needed to separate out the influence of career stage, number of papers read, reading expertise and experience on reading strategy.

Implications for practice

Our study was designed to explore what readers did when encountering a novel research paper, rather than evaluating any particular pedagogy. There are multiple published teaching strategies to support undergraduates with reading research papers (e.g. Hoskins et al., 2007, 2011; Kozeracki et al., 2006; Willmott et al., 2003). The disciplinary nature of literacy means science educators need to build time into their curricula to model expert reading strategies (Davies, 2018; Shanahan & Shanahan, 2012). The results of this study allow us to make the following recommendations for teaching practice. (1) Instructors should recognise that early-career readers may have a (very) limited prior knowledge on which to draw when reading, and that this may be a barrier to deeper engagement with research literature. Readers should be given time and support to create an appropriate schema of knowledge before being expected to read critically. For early encounters with the literature, instructors should select papers carefully to ensure they are appropriate. (2) Instructors should explicitly promote reading strategies that support a data-centric approach to reading, including interpretation of figures and tables. This may be most effectively achieved by including assignments that focus on developing academic reading in a disciplinary context. (3) Courses should include repeated opportunities for readers to increase their confidence when engaging with research papers, rather than relying on a single intervention. (4) Courses should allow inexperienced readers to model 'expert' reading strategies. This would be most effectively done by bringing novice and experienced readers together to openly discuss their reading, including strategies adopted and the frustrations of reading complex scientific text. (5) Postgraduate programmes should also incorporate structured support for scientific reading. This may be especially relevant for interdisciplinary researchers, who may need more support in reading outside their core discipline than is generally recognised.

Conclusions

We have explored how scientists at different career stages approach reading an unfamiliar scientific paper, using a case study within the biosciences. While our study does not capture the full depth of reading practices, it indicates that experienced scientists are more likely to read in a data-centric way, while inexperienced readers are more likely to use written narratives to inform their understanding. Experienced readers are also more likely to have a coherent schema of knowledge on which to base their understanding, and that lack of knowledge can be a barrier to deeper engagement for inexperienced readers. As such, we cannot assume that early-career readers interpret 'go and read a paper' in the same way as more experienced research-driven readers. If our pedagogical aim is for undergraduates to model 'expert' reading strategies, they need active support and scaffolding to prioritise their reading, particularly when it comes to engaging with figures and tables. STEM educators therefore have a responsibility to adopt effective pedagogies for developing scientific literacy, so that inexperienced readers can understand what we actually require from scientific reading.

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