Meeting the challenge of chemical language barriers in university level chemistry education

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The specific yet varied challenges chemical language presents to students learning the subject are widely recognised. However, to effectively engage a student population becoming increasingly diverse in terms of culture, language and prior knowledge chemistry educators must develop pedagogical strategies that address issues of language comprehension.

In this paper we discuss the body of literature that provides evidence of the multiple challenges that the language of chemistry presents students. These include: words in a scientific context, words with dual meaning, similar words and symbolic language. The chemistry learning triplet is used to illustrate how students must use chemical language to move between the macroscopic, sub-microscopic and symbolic levels. Combining evidence from our research and the wider literature we describe a novel model of linguistic demand in multiple dimensions that represents the challenge of chemical language. This model can be used to assess the linguistic demand of teaching resources and to focus the appropriate use of language and literacy informed pedagogical strategies.

Key words: Chemical language, literacy, chemistry learning triplet, linguistic demand

1. Introduction

"What I mean and what I say is two different things," the BFG announced rather grandly.

"Now let me introduce you to the snozzcumber."

Roald Dahl's children's story "The BFG"[1] (the Big Friendly Giant) features Sophie, a young girl, who befriends a giant whose language includes unique and unfamiliar terms, such as "gobblefunk", "slopgroggle", "snozzcumber" and "fizzwiggler". Of course, no-one understands the giant, and making himself understood is part of the fun of the story. Dahl's word play invents the BFG's vocabulary, engaging the reader in a make-believe world. Before reading this book, no one would have understood what a snozzcumber is or for what it is used. Similarly, chemistry has a vocabulary that describes and explains chemical phenomena to which students are introduced. Understanding this decodes the wondrous sub-microscopic world of atoms, molecules and their reactions. However, the unfamiliarity of chemical language means students meet many chemical snozzcumbers throughout their education, which may become a barrier to understanding. Developing fluency in using and understanding specialist vocabulary is essential if students are to learn chemistry.

The specific yet varied challenges of chemical language are recognised[2] (Markic and Childs, 2016). These may become barriers to student learning, particularly among students who are diverse in terms of culture, language and prior knowledge[3]. Brown[4] highlighted potential identity conflicts in which students may avoid scientific language as a tactic to maintain their cultural identity. These students employed several strategies to avoid using science discourse, including denying knowledge of answers and yielding speech opportunities to fellow classmates.

University level chemistry students' familiarity with and competence in chemical language is often assumed, but evidence indicates their fluency is mistaken. Undergraduate and graduate chemistry students[5] experience chemistry linguistic challenges. At all stages of education, students meet new concepts via linguistic terms they interpret and assimilate. The success of university chemistry education depends on recognising and addressing these challenges by implementing effective pedagogical strategies.

This paper reviews and discusses evidence relating to some challenges language of chemistry present, including the application of innovative language and literacy focused strategies utilised with UK-based students preparing for undergraduate study in a widening participation context. These students do not have the usual qualifications for undergraduate entry and study chemistry as part of a one year full-time pre-undergraduate foundation year. A novel model of multidimensional linguistic demand is presented that represents aspects of chemical language learning. This model promotes reflection on chemical language usage in teaching and designing language focused curricula. The evidence for each challenge is summarised next.

2. Multiple challenges in the language of chemistry

Scientific language is dense, cognitive language that is rich in technical terminology and discourse structures specific to context[6][7][8]. This makes learning science challenging for students from diverse backgrounds[9]. Consequently, authors express the opinion that the language is a greater barrier to learning science than the content itself[10][11]. Specific challenges identified include the following:

2.1 Scientific context

Studies report difficulties regarding students use of non-technical words in a scientific context. Gardner[12], for example, identified many non-technical words such as *contrast* and *simultaneous* which were inaccessible to students. Similarly Cassels and Johnstone[13], in a study of around 23 000 UK students, noted words used in scientific contexts were less well understood than in non-scientific contexts. For example, the word “volatile” seemed to be well understood when applied to people but poorly understood in a chemical context. Marshall, Gilmour and Lewis[14] and Pickersgill and Lock[15] reported similar findings and highlighted instances of students choosing the opposite meaning for some words such as scarce for abundant and longer instead of contract. In a study of over 1000 South African High School pupils, Oyoo[16] made similar observations. This highlights the importance of contextual clues in determining meaning.

2.2 Dual meaning

Rees, Kind and Newton[17] reported difficulties for students developing understanding of words such as *salt, neutral, weak* and *reduction* that have scientific meanings that differ from their everyday meanings, with which students are more familiar. This supports findings of previous studies, including Meyerson, Ford, Jones and Ward[18], Jasien[19] and Snow[20]. Song and Carheden [21], for example, demonstrated how college students struggled to retain scientific meanings of this dual meaning vocabulary. This demonstrates how, even if the meaning of words in the scientific context has been introduced and explained, the more frequently used everyday meaning can persist.

2.3 Similarity

In multiple choice tests students have been shown to confuse similar words such as *retract* and *contract*, *conversion* instead of *convention* and *negligent* instead of *negligible*[14,15,22]. More recently, Vladušić, Bucat and Ožić‘s[5] study of 82 Croatian undergraduate and 36 graduate chemistry students, found students mistaking words that are similar in appearance but have different meanings. For example, students confused *težište*, which means the “centre of mass in relation to electron distribution in bonding” with *težnja*, which means "aspiration". This has also been observed in the context of students providing scientific explanations of phenomena[23] using similar words but with different meanings. Examples include: *electronegative*, *negative* and *electron density*. This makes it hard to generate a coherent explanation and to determine the level of understanding.

2.4 Symbolic language

First year undergraduate chemistry students investigated by Marais and Jordaan [24] were unable to identify meanings of components of chemical equations correctly, including [NO_2] and $2NO_2$. Rees, Kind and Newton[17] also report persistent difficulties in students' understanding of symbolic language, for example, recognising that "H_2O" and "OH_2" are equivalent representations. These shortcomings make it very challenging for students to engage in and properly interpret chemical equations.

3. Language fluency

Undergraduate students' engagement with reading lists depends on their reading skills. Literacy research investigating development of reading skills[25] describes how fluent and skilled reading is a multifaceted process comprising language comprehension and word recognition. Language comprehension itself involves background knowledge, comprising facts and concepts; vocabulary in terms of breadth, precision, and links; language structures such as syntax; verbal reasoning requiring inference and use of metaphors and literacy knowledge of different genres. Word recognition relates to phonological awareness of syllables and phonemes, decoding and sight recognition of familiar words. Fluent reading of chemical text, therefore relies on developing subject specific skills in language comprehension and word recognition. Pyburn, Pazicni, Benassi and Tappin[26] demonstrated a correlation between general language comprehension ability and general chemistry performance and Rees, Kind and Newton[17] provided evidence that success in chemistry examinations correlated with student understanding of chemical language. Therefore, development of language comprehension and word recognition relies on chemistry educators incorporating appropriate strategies within their teaching so students are able to formulate and articulate coherent explanations of chemical phenomena.

4. Three levels of chemistry learning

Johnstone[27] represented chemistry learning occurring on three levels: macroscopic, that is what can be seen, touched and smelled; sub-microscopic, that is atoms, molecules, ions and structures; and symbolic meaning, representations of formulae, equations, mathematical expressions and graphs. Johnstone arranged these levels at the apexes of an equilateral triangle (Figure 1) to indicate equal, complementary significance. Teaching occurs "within" the triangle, under the assumption that all levels are equally well-understood. A successful learner must develop competence in inter-relating these three aspects, learning to move between levels often without notice or explanation. For a novice chemist complexity of thinking required may be too great.

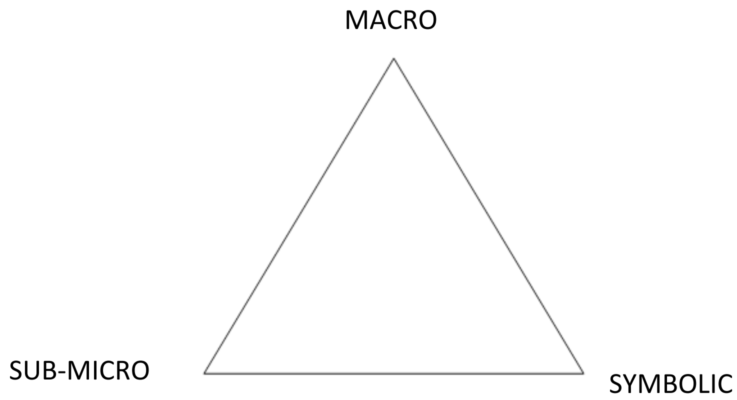

Figure 1 The chemistry learning triplet (Johnstone, 1991)

The chemical language required to move between these levels can be explored. Students in Rees's[23] study were invited to suggest words and symbols relating to describing and explaining a burning candle. Vocabulary ranged from names of objects and elements such as *oxygen*, to processes such as *combustion*, and concepts such as energy changes in a chemical reaction. The terms were classified using Johnstone's three levels (Figure 2).

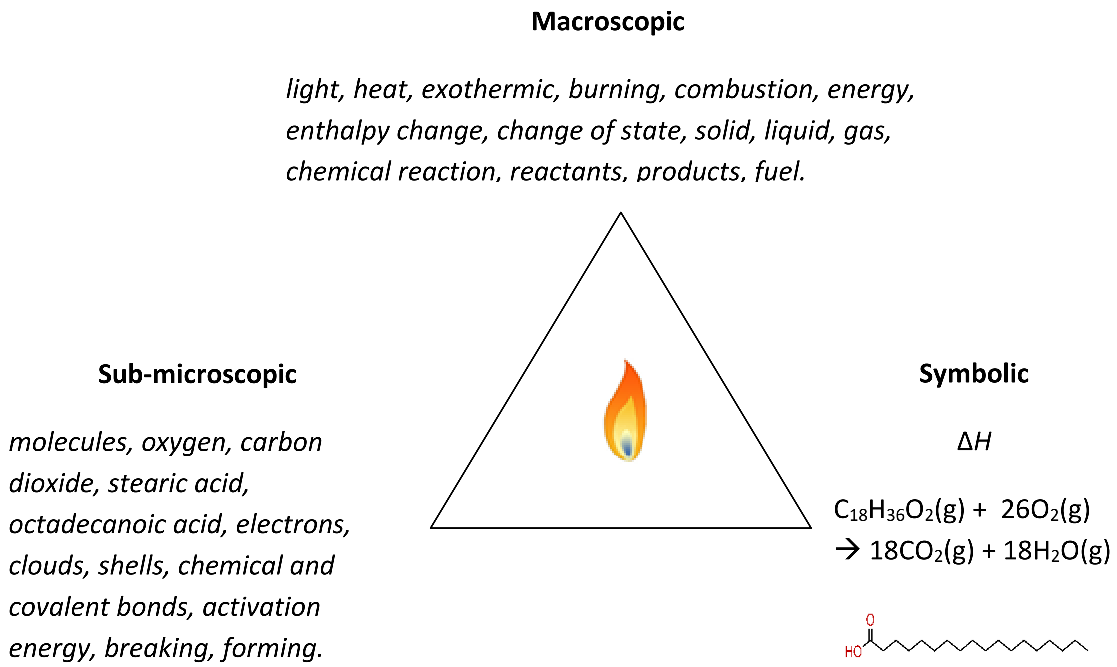

Figure 2 Vocabulary and symbols generated by potential undergraduates about a candle flame[23].

Therefore, in order to formulate an explanation requires use of a variety of language across the three levels. Chemical language occurrence across the three levels in teaching can be illustrated by considering course content. Figure 3 presents the text from one slide of a first year undergraduate lecture in a "chemistry for biologists" course. The text, analysed using Johnstone's model highlights that students are required to oscillate nine times between symbolic, macroscopic and sub-microscopic levels when interpreting the content. Combined with technical (*stoichiometry, moles*), non-technical vocabulary (*conserved, non-integral*) and sentence structure the text places high cognitive demand on readers.

Stoichiometry **– Molecules** and Moles

The atomic weight in grams of any **atom** contains the same number of atoms – approx. 6.022×10^{23} – this is called Avogadro's number.

This amount is called the gram molecular weight.

We can work out the **molecular weight** of any compound by adding the **atomic weights** of its **constituent atoms**

e.g. CH_4 = 12 + (4 x 1) = 16

(this is complicated in practice by **isotopic forms of the elements** making numbers non-integral)

The **molecular weight in grams** of any compound contains the same number of **molecules** - approx. 6.022×10^{23}

This amount is called the gram molecular weight or mole

To work out stoichiometries is now straightforward

CH_4	+ $2O_2$	→	CO_2	+ $2H_2O$
I molecule	**2 molecules**	→	**1 molecule**	**2 molecules**
1 x (12 + 1 x 4)	2 x (2 x 16)	→	1 x (12 + 16 x 2)	2 x (2 x 1 + 16)
16	**64**		**44**	**36 (atomic weights equal)**
1 mole	2 moles		1 mole	2 moles
16g	64g		44g	36g (*mass* conserved)

Figure 3 Text from one slide of a Year 1 undergraduate "chemistry for biologists" course on stoichiometry classified in terms of Johnstone's triplet. *(Permission to reproduce granted by Professor J. Gatehouse).*

Bold text = sub-microscopic, underlined = macroscopic, italicised = symbolic.

5. Linguistic demand in multiple dimensions

Lists of "difficult" words and specific types of words, such as those with dual meaning are available[28]. This section discusses how scientific words present students with learning challenges. These challenges go beyond whether or not a student understands the correct meaning of a word but extend into their ability to incorporate words into their oral and written explanations. To help address this, a model for assessing linguistic demand of chemical vocabulary in four different dimensions is proposed.

5.1 Interpretive

The **interpretive** dimension is the extent to which meaning can be determined directly from the word itself. To return to Roald Dahl, "Snozzcumber", for example, presents low demand in this dimension because the word contains "clues" from which meaning could be inferred. "Cumber" may be linked to the vegetable known as a "cucumber", while "snozz" may equate to "snot", the colloquial English term for nasal mucus. Hence, a snozzcumber could mean a revolting, slimy cucumber.

The interpretive dimension encompasses Sutton[29,30], who considers scientific words as interpretive tools. For example, *capillary* in the context of *capillary attraction*, presents high linguistic demand because the meaning is not immediately apparent from the word. Nor can meaning be determined by association with *blood capillary*; or from its Latin root (*of hairs*) without prior knowledge of Robert Boyle's[31] observation of water moving up glass tubes of "hair-like" thickness - capillary tubes. Other terms scoring highly in this dimension include *Le Châtelier's principle*, *Markovnikov's rule* and *the Aufbau principle*, because no indication of the process to which these refer is immediately apparent

Interpretive also relates to studies highlighting difficulties with words that have everyday meanings and different, specific meanings in science[17,18,19,20]. For example, the word *weak* in the context of *weak acid* scores high in this dimension because its meaning in this context as "an acid that partially dissociates" differs from its everyday meaning. In the context of *weak intermolecular forces*, however, *weak* scores lower because the meaning is synonymous with an everyday context of "something lacking strength and being easy to break".

In contrast, "*gas*" scores low in this dimension because of familiarity in an everyday sense such as "*I need some gas for the stove*" and similar meaning in chemistry "*the reaction produced a gas*". Therefore, *gas* is likely to be understood correctly in a chemical context. Thus the non-literal demand for *gas* is lower than for *capillary*.

5.2 Sub-microscopic

The second dimension is **sub-microscopic**. Students[23] find articulating explanations in the sub-microscopic domain difficult. This is because concepts are abstract, hard to visualise and require sub-microscopic vocabulary. *Electronegativity*, for example, presents challenges because explaining and understanding requires sub-microscopic level thinking. *Electronegativity*, therefore, has high linguistic demand in this dimension. *Gas,* in contrast, operates at the macroscopic level, so presents lower linguistic demand. However, modification of *gas* to *gas molecules* transfers the term to the sub-microscopic level, increasing the linguistic demand. Symbolic language is included within this dimension when sub-microscopic entities are referred to.

5.3 Similarity

The third dimension is **similarity** with other words. Rees et al., recorded instances of students using similar sounding words with different meanings such as *electron* and *electrophilic* or *interact* and *react*. Other studies have reported similar occurences[5,14,22]. A word that can be easily confused corresponds to greater linguistic demand. For example, students confuse *electronegative* with *negative* and *electron density*. Electronegative therefore, has a high linguistic demand. *Gas*, however, is less likely to be confused with similar sounding words so has a low linguistic demand in this dimension.

5.4 Multiple contexts

The fourth dimension is **multiple contexts**. Linguistic demand is increased when the same word can be used in multiple contexts with different meanings. For example, *strong* can be used in multiple contexts of *metals, intermolecular forces and acids*. The contexts generate different meanings, so linguistic demand is increased. *Gas*, however, has similar meanings in various contexts. For example, *the gas was contained under high pressure; the syringe filled up with a gas; propane gas has a low boiling point*. Therefore, linguistic demand for *gas* is low in this dimension. Rees, Kind and Newton[17] identified difficulties understanding words with multiple meanings such as *reduction* and *weak*.

6. Graphical representation of linguistic demand

These dimensions can be visualised graphically. The linguistic demand of a word is scored between 1 (low) to 10 (high) based on the scorer's judgement. A score is generated in all four dimensions for any given word. For example, if a word has lots of similar words that it can be confused with or if it has no interpretive value then it would score highly in the similarity and interpretive dimensions. Scoring process is not intended to produce consistent ratings as teacher judgment must be applied for specific educational settings. To enhance reliability, teachers who know the subject and capabilities of their students in a specific setting may score words or phrases independently then agree ratings by consensus[32]. Agreement can be high when such teachers make judgments about inexact qualities in this way.

Table 1 shows the scoring for *electronegative,* as determined by the authors*,* represented graphically in Figure 4. The scoring relates to a widening participation setting in which international and UK-based students without the usual entry qualifications for undergraduate study are taught chemistry as part of a one year full-time pre-undergraduate foundation course. This model of linguistic demand provides a mechanism for quantifying and investigating difficulties chemical words present in a specific learning setting. In the examples below, the size of the shaded area on each graph corresponds to the overall linguistic demand of each chemical term, while the shape points to the impact of specific dimensions. Examples are shown for words which are *electronegative*, *electrophilic*, *gas* and *weak*.

Linguistic dimension	Score	Explanation
Interpretive	5	The first part of the term indicates the involvement of electrons but the second part does not provide further explanation of the meaning *i.e.* the ability of an atom to attract the pair of electrons in a covalent bond.
Sub-microscopic	10	Operates exclusively in the sub-microscopic domain.
Similarity	10	May be confused with similar terms such as *electron density* or *negative*.
Multiple contexts	1	The term is not used in different contexts with different meanings.

Table 1 Linguistic demand for *electronegative* in four dimensions in a widening participation context

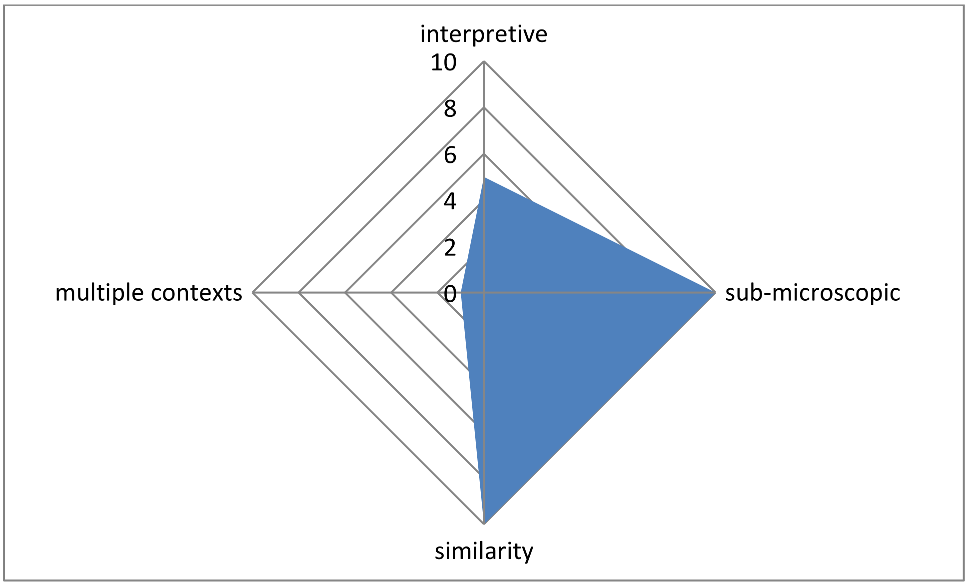

Figure 4 Linguistic demand for e*lectronegative* in four dimensions, in a widening participation context

Electronegative exhibits high linguistic demand in the sub-microscopic and **s**imilarity dimensions.

The diagram for the word *electrophile* is shown in Figure 5. Like electronegative, electrophile is high rated in the sub-microscopic and similarity dimensions. The interpretive dimension scores lower for *electrophile* than *electronegative.* This is because the meaning of *electrophile* can be determined assuming knowledge of the suffix "*phile*", that is *electrophile – electron loving*. Although e*lectron loving* is differs from a dictionary or examination definition of an electrophile as "an electron pair acceptor", this guides students to the correct meaning.

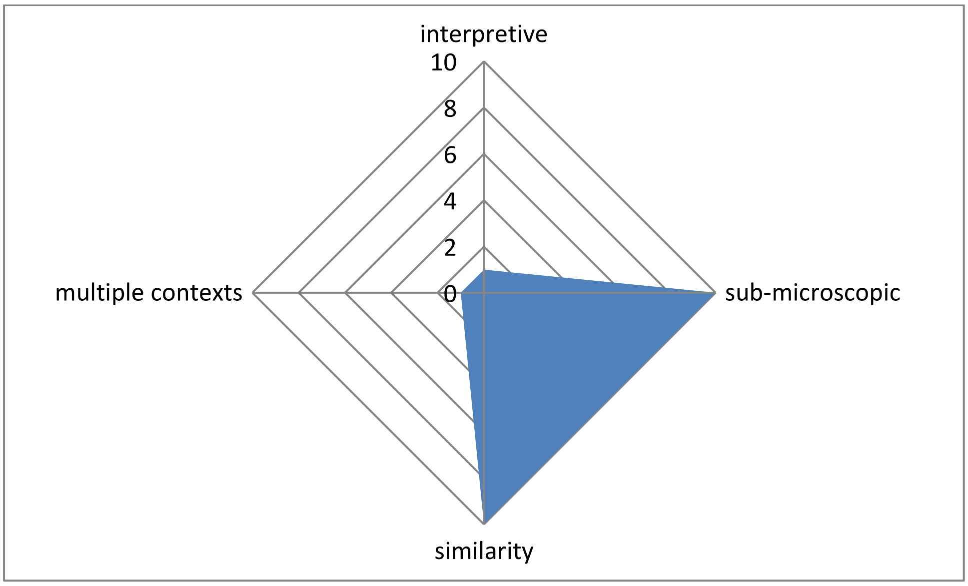

Figure 5 Linguistic demand for *electrophile* in four dimensions in a widening participation context

Gas scores low, as determined by the authors, in all four dimensions (Table 2) and the linguistic demand graph defines a much smaller overall shaded area (Figure 6).

Linguistic dimension	Score	Explanation
Interpretive	1	The term readily associated in everyday language and Greek origins enhance meaning.
Sub-microscopic	2	Operates in the macroscopic level except when collocated with molecules.
Multiple contexts	1	The term means similar things in different contexts.
Similarity	1	There are no terms that it can be readily confused with.

Table 2 Linguistic demand for *gas* in four dimensions in a widening participation context

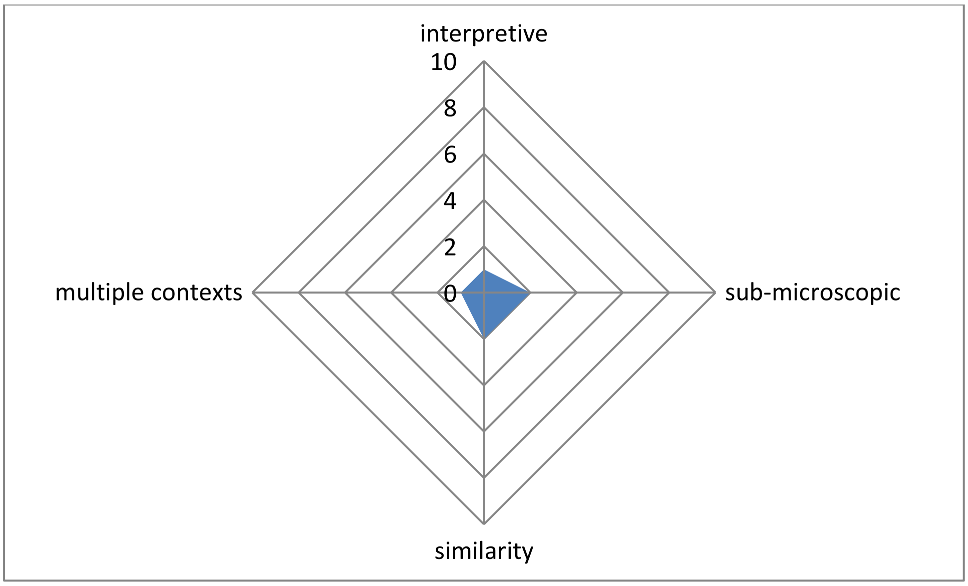

Figure 6 Linguistic demand for *gas* in four dimensions in a widening participation context

Applying this idea to dual meaning vocabulary such as *weak,* the graph covers a large shaded area indicating high overall linguistic demand (Figure 7).

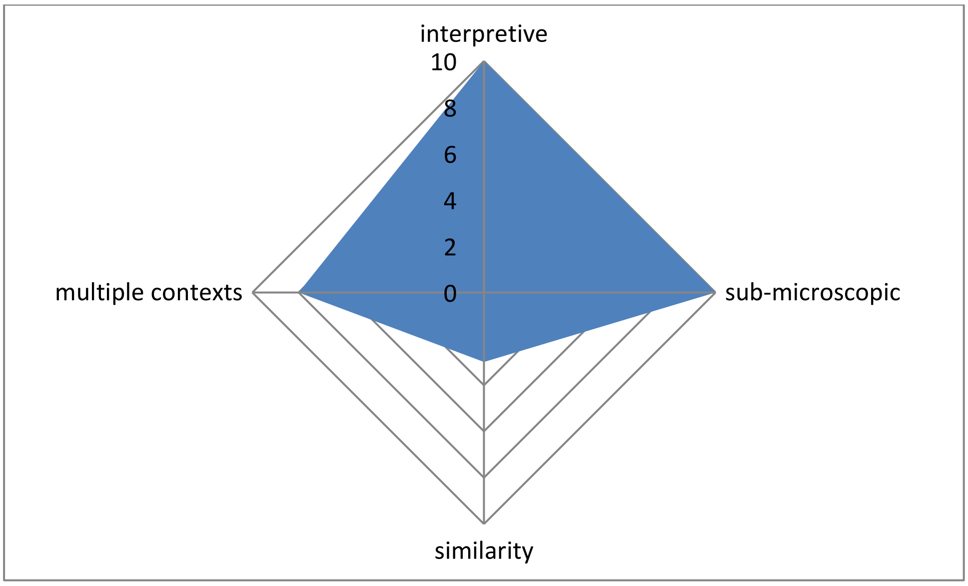

Figure 7 Linguistic demand for *weak* in four dimensions in a widening participation context

The application of this model in chemistry education has value by emphasising where difficulties lie and where specific activities should be targeted that support student learning (see Section 7). The model can also be applied to estimate linguistic demand of the content of lecture presentations such as Figure 3, student materials and textbooks. When used in conjunction with existing, general tools for measuring readability, such as Flesh Reading Ease and Flesh Kincaid Grade Level readability scales, the linguistic demand model provides a potentially valuable method for ensuring that materials presented to students utilise language appropriately. Where linguistic demand is found to be high, a review may make a resource more accessible to students. For example, the content in Figure 3 could be analysed in terms of linguistic demand and then modified to reduce this demand. Further work is needed to establish the validity of the model in terms of the impact of the different dimensions in different contexts. This would support the accessibility of chemistry to a wider and more diverse student population.

7. Teaching with respect to the linguistic dimensions

Studies have often either identified one aspect of word difficulty, such as dual meaning[21], or classified scientific words in to different categories[28]. The linguistic demand model presented above represents the analysis and classification of chemical language difficulty in multiple dimensions. This permits teachers to interpret chemical words in terms of the linguistic demand they present for learners. By considering chemistry learning from this standpoint, the potential arises to teach practice from a "linguistically informed" position, raising educators' awareness of chemical language and pedagogical approaches to support students. Table 3 provides examples of language and literacy focused strategies highlighted by chemistry educators. For example, a topic containing numerous words with high interpretive demand requires teaching strategies that address this, such as developing understanding of roots and origins of words[17,29].

When sub-microscopic linguistic demand is high, such as for *electronegative*, teaching strategies that help students relate to and visualise interactions are recommended. These include role play allowing students to "represent" electrons and modelling of atomic structures using classroom materials and via computer simulations[33].

Meanings of words with high demand in the similarity and multiple context dimensions can be taught by provision of opportunities to practise word usage. These include word games, dialogical approaches and peer feedback. Teaching focusing on scaffolding tasks that permit students to practise language usage (verbally and written) are also valuable. Corpus linguistics, the study of language patterns in a body of texts, enables investigation and exemplification of correct chemical language usage in multiple contexts[17].

Understanding of scientific language		
Strategy	Explanation	Reference
Combining vernacular and non-vernacular (double talk)	When a speaker assumes someone does not understand one version of a term and chooses two versions of the same idea. For example, when developing understanding of the word "classified" the teacher states "you've classified, you've decided that things go in different groups".	Brown and Spang[34] Lemke[6]
Decoding skills	Developing knowledge of Latin and Greek roots so that new unfamiliar vocabulary can be decoded.	Herron[35] Rees[17]
Multimedia	Engagement in images, animations, virtual models.	Mayer[36] Rees[17]
Word games	Use of word games to increase familiarity with chemical vocabulary.	Herron[35] Rees[17]
Exemplification – corpus linguistics	Use of a scientific text database to illustrate word usage in context.	Rees[17]
Cues	Inferring meaning from context.	Herron[35]
Interpretative meaning	Exploring the stories behind the names for words to enhance their value as interpretive tools and not just labels for processes or substances.	Sutton[29] Rees[17]
Developing initial understanding of scientific ideas		
Strategy	Explanation	Reference
Use of vernacular prior to non-vernacular	Where possible, ideas are introduced using vernacular language prior to introducing non-vernacular language. This can reduce issues of anxiety and identity and ensure that content understanding is established prior to linguistic understanding.	Brown and Spang[34]
Discursive strategies	Guided and structured activities to promote meaningful discussion incorporating and extending language usage.	Lemke[6] Edwards and Mercer[37] Carlsen 2007[38]
Engaging with scientific text		
Strategy	Explanation	Reference
Close reading strategies	Development of analytical reading strategies to focus reading	Brown and Concannon[39]
Scaffolding activities	Staged reading comprehension activities to develop analytical reading	Wellington and Osborne[28]
Rules of inference	Developing understanding of information that can be inferred such as from chemical equations	Herron[35]

Table 3 Summary of language and literacy focused pedagogical strategies.

8. Summary and Outlook

Language is dynamic and evolves over time. For example, *sulfuric acid* is no longer referred to as *spirit of vitriol*. Chemical language adapts as discoveries are made and incorporates societal change, extending the already extensive vocabulary of terminology. There is a need to make this language accessible to learners if chemistry is to engage with a broader and more diverse student body. The multi-dimensional model proposed provides a mechanism for identifying terms that present high linguistic demand. For novices, consideration should be given to changing these for words that present lower overall linguistic demand. *Electronegativity*, for example, exhibits high linguistic demand in interpretive, sub-microscopic and similarity dimensions. Substituting *electronegativity* with *electron pulling power* introduces the notion using accessible language with lower linguistic demand. Electron pulling power can be linked to the higher demand word, allowing students to transition their understanding[34].

This paper highlights the significant language-based issues raised by widening participation in chemistry, ensuring teaching and learning meets the needs of a diverse student cohort. Helping students “gobblefunk” in addressing the “snozzcumbers” of chemistry is essential to their learning experience. As the BFG found in relation to his language, no-one is a native “chemistry speaker”. Therefore, all chemistry educators must incorporate pedagogical strategies that aid assimilation and articulation of chemical language.

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