Lexical Ambiguity in Evolutionary Discourse: Implications for Teaching, Learning, and Assessment

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Language in Science

Written and spoken language are the primary means through which fundamental scientific ideas – such as evolution and natural selection – are communicated, assimilated, and accommodated through scientific and science education history (Lemke, 1990; Kaplan, Fisher & Rogness, 2009). In addition, language often occurs in multiple formats and contexts (e.g., graphs, pictures, equations, and text) that are often used interchangeably to represent abstract conceptualizations of scientific phenomenon (Brookes & Etkina, 2007; Lemke, 2000). Furthermore, specialized scientific terminology is often intermixed with and recruits words from everyday discourse (cf. Ryan, 1985), resulting in a complex network of discipline-specific discourses containing specialized meanings that have little or no distinguishing features.

As students develop increased understanding of more complex scientific processes, consideration of scientific language and literacy become more important. Students must understand and be able to communicate about the various nuances of biological phenomenon, such as evolutionary change by natural selection, genetic drift, and artificial selection. As students gain competency in such concepts, they progress through levels of understanding of scientific words and meanings. In natural languages, there are many words with multiple meanings that are only distinguishable by associated informational factors such as context and meaning frequency (Zempleni, Renken, Hoeks, Hoogduin, & Stowe, 2007). Words often have core meanings that trigger a specific mental representation (dominant meaning), but they may also have a set of characteristics that branch off from the core definition, creating multiple representations and meanings for a single term (Kaplan et al., 2009). This is known as *lexical semantic ambiguity*, and can be problematic when learning a new and specialized language, such as science.

Understanding Multivalent Terms

Lexical ambiguity is a particularly troublesome attribute of evolutionary discourse (cf. Kaplan et al., 2009; Nehm, Rector, & Ha, 2010). In their early use of scientific discourse, novice learners often incorporate scientific terminology (e.g. naming) without a full mental representation or understanding of the meaning behind such language (Schramm, Wilke, Hartley, & Anderson, 2010). “Adapt,” “develop,” and “pressure,” for example, all have very different meanings in evolutionary biology than in everyday language. Moreover, the meanings of some evolutionary terms are considered implicit and remain underdefined in the scientific community (e.g., ‘evolutionary pressure’; Nehm et al., 2010). This use of ambiguous words is a pervasive feature of novice discourse in many areas of science, including evolutionary biology, and studies have shown that students are often unable to distinguish between the nuances of scientific language that provide accurate scientific explanations (e.g. Clough & Wood-Robinson, 1985). Conversely, while expert (“native”) speakers will encounter ambiguous terms in similar frequency they are less likely to perceive them as containing ambiguous meaning (Zempleni et al., 2007). Collectively, these factors account for how language may complicate communication of scientific concepts and inhibit scientific learning and valid assessment of knowledge (Durkin & Shire 1991; Lemke, 1990; Kaplan et al. 2009; Mead & Scott, 2010a,b).

This paper focuses on the issue of lexically ambiguous language within evolutionary biology. The study investigated evolutionary discourse practices associated with the notion that multivalent terms are numerous and diverse in scientific language. These multivalent terms are often ambiguous in meaning, resulting in ambiguous explanations of evolutionary change. Although many multivalent terms occur in biology, this study examined five commonly used terms that were also characterized by different *types* of ambiguity: (1) A term that has ambiguous meaning in evolutionary scientific discourse *but has unambiguous meaning in everyday* discourse ("pressure"); (2) Terms that have unambiguous—but different--scientific meanings *and* unambiguous everyday meanings (e.g., "adapt" and "select"); and (3) Terms that have *no apparent scientific meaning* but have clear everyday meaning (e.g., "need" and "must"). Following a biology course designed around evolution as the core idea, this study examined three aspects of evolutionary discourse and evolutionary explanation: (1) the frequency of students that spontaneously use these multivalent terms in their responses to questions of evolutionary gain scenarios, (2) students' definitions and explanations of each of the five multivalent terms, and (3) holistic response change from students' initial explanations to their follow up explanations.

Research Methodology

This study explored undergraduate biology majors' use of and reasoning about five multivalent terms (pressure, adapt, select, must, and need) used in evolutionary explanations using a validated set of open response items (Nehm et al., 2010). Previous studies using open-response evolution assessments noted that many responses were difficult to score because of the intrinsic ambiguity of evolutionary language (Nehm & Schonfeld, 2008). For example, how should science teachers and researchers interpret students' responses such as: "The *pressures* caused the species to *adapt* because it *needed* to survive"? Understanding the contexts of term use may be used to resolve such ambiguity, but it can be difficult to judge accuracy based exclusively on context cues. Interviews and oral discussions provide the option of asking follow-up questions to student statements, such as: “What did you mean by adapt?” or “What do ‘evolutionary pressures’ mean to you?” However, such methods can be impractical for large classes or written responses.

Responses for this study were gathered using the online Assessment Cascade System, which captures initial responses to questions in an open text format, and also “mines” students’ responses (in real time) for designated terms of interest. Students who spontaneously used a multivalent term in their evolutionary explanations were to explain what they meant when they used it. The sample collected by the ACS included 1282 responses generated by 320 undergraduate students intending to pursue biology related careers. These responses consisted of 716 initial evolutionary explanations and 747 follow-up responses. The students in the study were about to complete the second quarter of an introductory biology sequence for majors at a large public research university in the Midwestern United States. The average age of the participants was 20.4 years, with 55.3% of the sample female. Non-Hispanic Whites comprised the majority of the sample (76%) with 24% minority (African-American, Latino/a, Asian, and Native American). The average course grade (on a 4.0 scale) was 2.83 and participation consent was > 80%.

In order to analyze the composition and structure of students’ explanations involving specific terms, we first designed a set of independent rubrics (one per multivalent term) according to a list of common (Oxford English Dictionary) and scientific definitions (Campbell & Reece, 2008). The first rater coded the data using the rubrics as a framework for coding student responses that included each multivalent term. A second rater independently used this assessment rubric to blindly score all student responses for the specified multivalent models (as well as holistic judgment of the scientific accuracy of each initial and follow-up response). In some cases, students provided a definition that could not be classified. This occurred when the researchers could not infer a meaning from what was written in the response or when no definition was given. Initial Kappa agreement values were > 0.75 between raters for all terms and holistic answer scores, and all coding discrepancies were subsequently resolved via deliberation prior to data analysis. Statistical analyses were performed in PASW (SPSS, Inc.) and JMP (SAS, Inc.).

This sample of student essay responses was used to investigate three research questions about lexical ambiguity in students' evolutionary discourse:

1. To what extent is the type of lexically ambiguous terminology associated with particular evolutionary prompts (e.g., Type I, II, III)?
2. To what extent are lexically ambiguous terms associated with accurate student explanations of evolutionary change?
3. To what extent does the use of follow-up prompts enhance interpretation validity?

In order to examine the effectiveness of the follow-up prompt in resolving lexical ambiguity in student explanations, a composite evaluation score was calculated to represent the collective scientific accuracy for students who spontaneously used multivalent terms. The composite evaluation was calculated by averaging the initial score (0=inaccurate, 0.5=ambiguous, and 1=accurate) with the follow-up score for each explanation containing a multivalent term. This score then represents the scientific accuracy of the undivided student explanation (initial + follow-up). This composite evaluation can be used to determine the effectiveness of the follow-up in resolving ambiguity and testing interpretation validity.

Results

Students' Use of Ambiguous Language in Evolutionary Explanations

Analysis of the 1282 student explanations of evolutionary change revealed that 81% of students spontaneously used one or more multivalent terms (e.g. selected, needs, etc.). Term types I and II were the most frequently employed in student explanations, representing 78% of student responses containing ambiguous language. Initial scoring (not taking the follow-ups into consideration) revealed that 43.5% were scientifically inaccurate, 36.4% were ambiguous or non-informative, and 20.1% were accurate. The following section reviews examples of students' follow-up responses in order to demonstrate the diverse meanings represented by a single word. We first review, in students' own words, the various meanings that they connect to the same terms.

Students' Conceptions of Evolutionary Change

Analyses revealed multiple meanings for the five relatively common terms examined in this study. Conceptualizations of evolutionary change that incorporated "selective" or "pressure"-related ideas represented the majority of explanations (Term Types I & II). However, words and meanings recruited from everyday language, such as need, also resulted in student explanations that were erroneous in evolutionary contexts.

Term Type I - In follow-up responses, when asked what they meant when they used "pressure" in their explanation, many students explicitly stated that pressures were the direct cause behind death or change (evolutionary or small-scale): "Evolution is a process by which pressures exerted on biotic life and…caused the species to evolve." Other students conceptualized pressures as "forces of nature" that are the cause of a *need* for adaptation or acclimation. In contrast to "pressure" as a cause ideas, some students conceptualized evolutionary pressures to be a ‘placeholder’ for a long and diverse list of possible biotic and abiotic factors and interactions that may have occurred in the natural environment: “Pressures in this case would include temperature, presence or absence of wind, moisture, sunlight and area of dispersal.”

Overall, the data indicated that the word “pressure” means different things to different students. For some it may serve as a guiding or directive force that produces adaptation or evolution. Alternatively, some students used “pressures” to represent scientifically acceptable shorthand for the various environmental factors that may have an impact on differential survival.

Term Type II - In follow-up responses, when asked what they meant when they used “adaptive” terminology, some students equated this type of term with direct, active, and immediate change, such as “changing itself to suit the environment around it.” Other students referred to “adapted” as a state permitting survival in a particular environment: “The organisms [are] more fit and able to sustain life in [their] environment.” Conceptualizations of this kind are akin to acclimation in an environment (e.g., putting on a sweater in a colder environment), and are not concordant with evolutionary reasoning about biological adaptations. Student follow-ups that defined “adapt” as a process of accumulating beneficial, heritable characteristics over multiple generations were representative of accurate, scientific explanations. Overall, three general conceptions appeared to be tied to the word “adapt.”

Student responses to follow-up questions prompting them to explain what they meant when they used the word “select” (and related terms), often referred to a process of choosing or being chosen by some individual or process. For example, “picking between two or more choices” and “selection is how [something] selects or chooses the trait” represent two definitions that indicate that there is a choice or decision that is made regarding the trait in question. In contrast, other students connected the process of "being selected" to a "need" or "pressure" from the environment. In such cases, the change was desirable to the organism.

Follow-up items for term Type II revealed a diverse set of meanings represented by the same terms. Specifically, "adapt" could mean a direct 'adjustment' to changing conditions, a process of accumulating beneficial traits over time, or simply the state that permits survival. These meanings, while connected, represent distinct interpretations of the term "adapt" in evolutionary contexts. A similar pattern was found for "select," which could mean the act of 'choosing' or a state of being selected. Thus, terms in this category seem to represent the actions of an individual rather than of the environment (as in *Type I*). In addition to individual action, there is often an element of *intent* or *conscious response* to the actions of other individuals or to environmental factors.

Term Type III – The most common definition of '*must'* used by students suggests the multivalent term is a "placeholder." When asked what they meant by their use of 'must', many students indicated that they did *not* intend to indicate a necessity or preference for evolutionary change. Rather, in these cases 'must' was meant as a statement or fact, rather than a requirement or necessity. For example, "an organism wouldn't still continue to have this change if it were not beneficial to its survival and reproduction, so we know that it must help the organism."

Unlike the previous categories, student meanings of this type were much less diverse. The most common student explanation for "need" was that need or desire for a trait directly resulted in evolutionary change. Need was a response to the environment, such as: "The longer tarsi animals [were] the ones surviving, [therefore] the longer tarsi were needed for survival." Some students interpreted need as equivalent to the pressures in the environment: "…the term need most closely means environmental pressure." Overall, although *need* was considered to always be an inaccurate component of evolutionary explanations, there were some instances in which students were using the word in a way that was consonant with scientific understandings. Nevertheless, most uses of Type III terms were inaccurate, even after consideration of the follow-up responses.

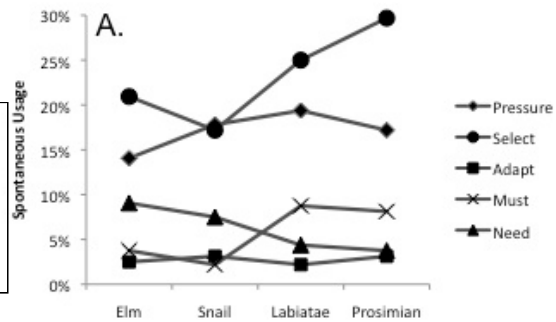
Contextual Effects on Term Use

In addition to investigating the various meanings students ascribe to the terms of interest, this study examined the frequencies with which these terms were used and their association with the different prompt contexts. Student use of “pressure” and “adapt” were fairly consistent across the four assessment items (Mantel-Haenszel test: pressure, $p=0.26$; adapt: $p=0.83$), while the usage of “select,” “need,” and “must varied significantly across prompts (Figure 1A). Two groups of terms were identified based on their frequencies: high-use terms (Figure 1B; “pressure” and “select”) and low-use terms (Figure 1C; “adapt,” “need,” and “must”). Within the high-use terms, accuracy was significantly context dependent in initial student responses (Ordinal Logistic Regression, “pressure” $p=0.0002$ and “select” $p=0.0005$), but not significantly so in the composite evaluations (“pressure” $p=0.20$ and “select” = $p=0.59$) (See Figure 1C). Similar patterns cannot be reported for the low-use terms because initial use of these terms was low and highly variable.

Students’ Conceptual Accuracy

Of the many meanings represented within the students’ representations of the five multivalent terms, very few were scientifically accurate. However, student accuracy did increase for the majority of terms with the addition of the follow-up response (Figure 2C). While accuracy of multivalent language varied by term (Figure 2A), it was not significantly related to any self-reported demographic variables (e.g., gender, age). For some terms, percent accurate usage was significantly related to course grade. Students with a high accuracy rate for “pressure” and “adapt” were significantly more likely to have a higher course grade (Table 1). Conversely, “need” was the only term that did not demonstrate a positive trend of accuracy versus grade. Note that “need” is rarely an appropriate term for evolutionary explanations, and is almost never used in a scientifically accurate manner (see Figure 2). Interestingly, “need” shows a reverse trend with course grade, with ‘A-students’ avoiding the use of the word (13%) while 35% of the ‘C or below students’ used “need” in any of the four question contexts (see Table 1).

Figure 1: Context effects on frequency of ‘multivalent’ term use in student explanations. A. Percentage of students who spontaneously used the terms across each question type. B. Context Effects on Low-Use Words. C. Context Effects on High-Use Words.



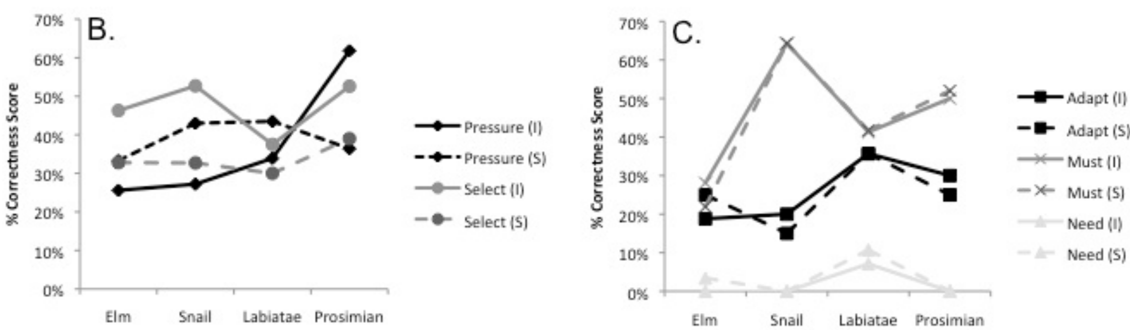
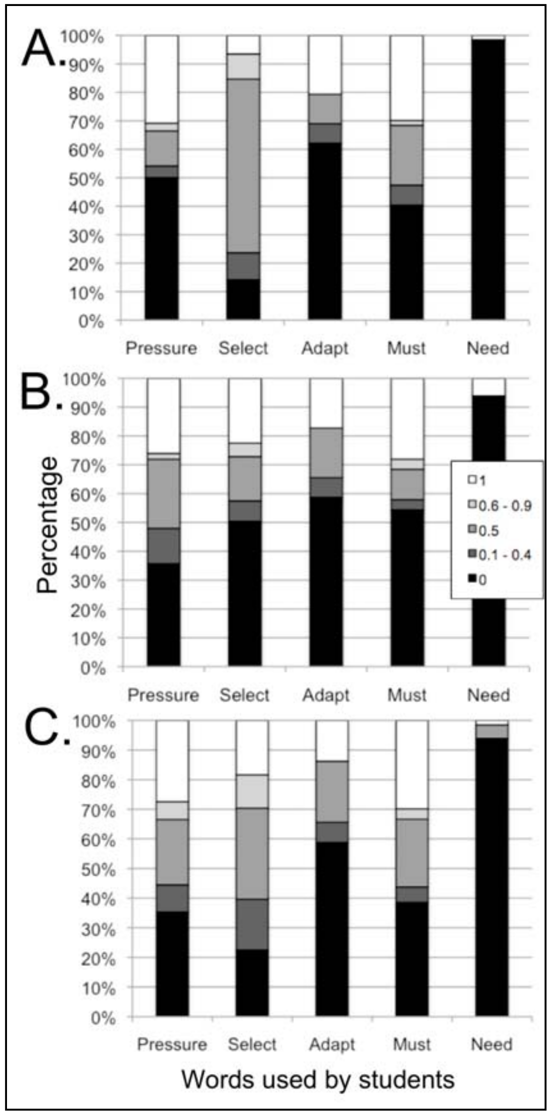


Table 1. Relationship of course grade to the percentage of accurately used multivalent terms. Table gives average percent accuracy ± s.e.m. in composite evaluation.

Grade	Pressure	Select	Adapt	Must	Need
A N=86	51.8±6.3% n=41 (48%)	54.3±5.1% n=47 (55%)	52.8±16.9% n=6 (7%)	56.3±10.1% n=16 (19%)	4.5±4.5% n=11 (13%)
B N=165	40.1±4.8% n=75 (45%)	45.7±3.9% n=80 (48%)	22.1±8.5% n=17 (10%)	44.5±7.5% n=32 (19%)	3.3±3.3% n=30 (18%)
C or below N=68	25.3±6.9% n=30 (44%)	39.2±5.1% n=42 (62%)	8.3±8.3% n=6 (9%)	27.8±14.1% n=9 (13%)	4.2±2.9% n=24 (35%)
Rank correlation	0.24	0.16	0.44	0.22	-0.05

Figure 2: Accuracy scores for student conceptions of multivalent terms. An individuals' accuracy score represents the average of their response accuracy across each prompt in which they used a multivalent term. Responses judged as accurate were scored a '1', ambiguous as a '0.5' and inaccurate a '0'. A. Accuracy of initial student responses; B. Accuracy of follow-up responses; C. Composite evaluation of student responses.



Holistic Change of Students' Responses

The value of the follow-up prompt for determining students' evolutionary understanding was dependent on the term being examined. Explanations containing "pressure" and "select" were examined using the composite evaluation (combined initial and follow-up responses). While the majority of student response scores remained unchanged, a significant proportion of those that did change resulted in the resolution of ambiguity (Figure 3). Student responses containing the term "select" changed more often than those containing "pressure." Of the responses containing "select," evaluations of accuracy changed 47% (N=139) of the time. Importantly, 83% of these changes resulted in the resolution of ambiguity rather than a change in accuracy. Responses containing "pressure" only changed 20% (N=43) of the time, with 16% of these resolving ambiguity. Overall, it appears that ambiguity resolution is the most common function of the follow-up items.

In summary, these analyses revealed multiple meanings for the five relatively common, yet ambiguous, words examined in this study. Student conceptualizations of evolutionary change that incorporated "pressure" or "select" represented the majority of explanations affected by the lexical ambiguity of evolutionary language, and terms and meanings recruited from everyday discourse (e.g., "need") most often resulted in student explanations that were scientifically inaccurate. Therefore, not only do students hold multiple meanings of scientific terms, they often utilize language and meanings that detracts from their understanding of evolutionary processes.

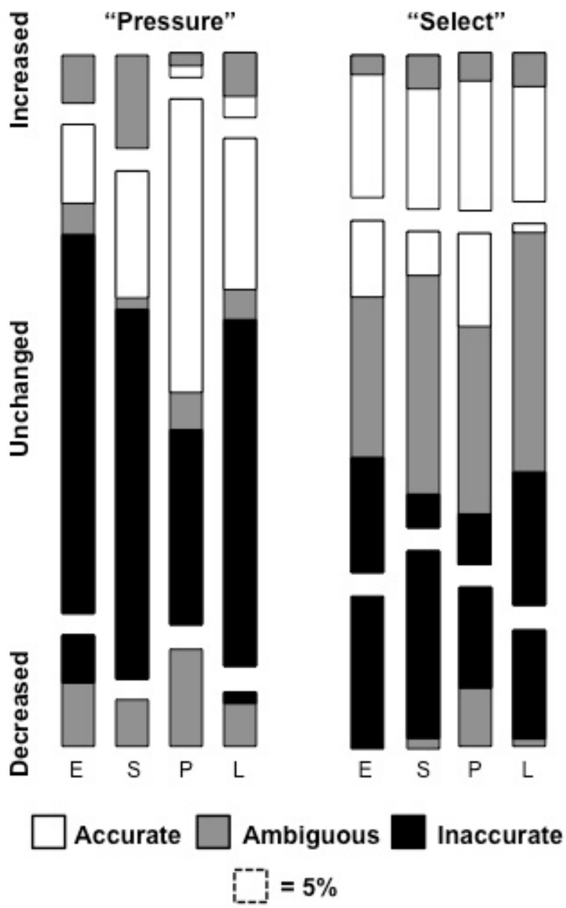


Figure 3:Holistic change in accuracy of student responses. Students' initial (I) and synthesis (S) response scores were compared to determine the effectiveness of the follow-up prompt in changing the interpretation of student responses. Initial and synthesis responses were scored as accurate (C), inaccurate (N), or ambiguous (A) and then compared. The accuracy of student responses either *increased* (top to bottom: NI → AS; AI → CS), remained *unchanged* (top to bottom: CI → CS, AI → AS, or NI → NS), or *decreased* (top to bottom: AI → NS; CI → AS).

Conclusions

Previous studies of lexical ambiguity in science education have demonstrated the constraints that words containing multiple meanings can have on student understanding and acquisition of concepts (e.g. Abrams, Southerland, & Cummins, 2001; Southerland, Abrams, Cummins, & Anzelmo, 2001; Nehm et al., 2010). The work presented in this study demonstrated that (post-instruction) many undergraduate biology majors spontaneously employed multivalent concepts in their evolutionary explanations, and the majority of these explanations were scientifically inaccurate and representative of naïve ideas. Accordingly, it appears that many students in our sample who are emerging from introductory biology coursework appear to have a tenuous grasp on evolutionary language and how to appropriately utilize it in causal evolutionary explanations.

The results of this study suggest that the five terms investigated are problematic and ambiguous for different reasons. Each term had a variety of meanings ascribed to it by introductory biology students, but of the three groups reviewed in this study, Type I (“pressure”) and Type II (“select” and “adapt”) concepts were the most prevalent. Despite being terms that have relatively common scientific meanings, students rarely incorporated terms from these categories into their explanations in a scientifically accurate manner. More prevalent was the use of ‘alternate meanings’ borrowed from everyday language. In fact, the vast majority of inaccurate definitions seemed to be a direct transfer of everyday meanings to an interpreted scientific meaning. It is apparent from these findings that students are unequipped to distinguish the nuances of scientific language and suggests that the ambiguity of scientific discourse is a major barrier to the development of accurate models of evolutionary change.

Examination of the students’ initial and follow-up responses demonstrate that the majority of students are consistent across responses, however a sizeable minority were not and the use of the Assessment Cascade System resulted in the resolution of initially ambiguous responses. Open-ended assessments valuable for providing insight into student understanding, but are problematic if the are not accurately representing students conceptual understanding of complex processes. While open-ended response items allow students to construct their own explanations, if students are “naming” processes without “explaining” them, then assessments are not actually measuring students’ conceptual understanding but rather their ability to utilize lexically ambiguous terms. As this study demonstrated, the validity of assessments attempting to measure students’ conceptual understanding of evolutionary knowledge would benefit from the use of follow-up questions.

Acknowledgments

I thank my advisor Ross Nehm, Dennis Pearl for statistical advice, Minsu Ha for help with scoring, Judy Ridgway for help with data collection, and the National Science Foundation (REESE 0909999 – Nehm) for funding this study.

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