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Using Inquiry To Break the Language Barrier in Chemistry Classrooms

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S Supporting Information

ABSTRACT: A guided inquiry lesson intended to support the linguistic and conceptual development of English language learners (ELLs) in a small, cotaught, high-needs secondary setting is presented. Collaborative groupings based on language and content ability coupled with an emphasis on student−student discourse and a hands-on investigation appeared to contribute to the positive outcomes that were observed on a written assessment. The phenomenon of code switching, where students spoke in their native tongue at times of apparent high cognitive demand, was observed. Implications of the approach used in this lesson for teaching chemistry in culturally diverse settings are discussed.

KEYWORDS: *High School/Introductory Chemistry, Inorganic Chemistry, Collaborative/Cooperative Learning, Inquiry-Based/Discovery Learning, Atomic Properties/Structure, Magnetic Properties*

■ INTRODUCTION

In discussing the science writing heuristic approach, Norton-Meier stated the following basic tenet: "There is no science without language".[1] Also, at the end of the same chapter, Norton-Meier notes, "While elementary schools struggle to put science into the curriculum, middle and secondary schools struggle to see science as having anything to do with language—yet it is critical for their subject".

Against this backdrop comes a renewed call for a scientifically literate citizenry in reports from the National Science Board and the President's Council of Advisors on Science and Technology.[2,3] Estimates from large-scale survey data of our nation's public schools place chemistry as the science course taken by more students (>2,500,000 as of 2007) than any other except biology.[4] An increasing proportion of our precollege classrooms are attended by students whose native language is not English,[5,6] but little has been reported about the efficacy of current approaches related to the success of these students within chemistry learning environments.[7,8] Tobin and McRobbie reported on the experiences of two Chinese students enrolled in a grade 11 course in Australia using a narrative framework and argued that a lack of English competency presented various challenges that likely impacted both their performance and their disposition toward future study in the subject. Flores and Smith described the experiences of 17 native Spanish speakers enrolled in a high-minority population high school near the United States−Mexico border after coding individual clinical interview data.[8] Among their major findings was the difficulty that non-native speakers had with conceptual development in the course as they had to navigate so many unfamiliar words, ideas, and representations in a language (English) that was also foreign. Also, there existed some challenges to developing competency in chemistry literacy as they did not identify with English as "their language" and were not confident practicing the language during class. Although limited in their number and scope, both studies identified trends that are likely relevant to the teaching and learning of chemistry involving English language learners (ELLs). While these studies indicate some of the challenges to making science (in particular, chemistry) accessible to non-native English speakers, additional studies of the relative experiences and successes of ELLs compared with their native-English-speaking peers are needed to provide insight into how to support the diverse needs of students enrolled in precollege chemistry courses across the country.[9]

Unfortunately, too often teachers are not formally trained to recognize how the learning demands of ELLs differ from those of their peers or how to provide the necessary scaffolds to ensure equitable access to the course content.[10,11] As a result, there can be a lack of awareness of how critical the influence of linguistic and cultural characteristics is to a student's learning, and even rudimentary differentiation and accommodations are not made. For students not having the shared experiences of culture and language as their teachers and colleagues, they face the complexity of learning a new spoken and written language and the nature and practices of a science discipline, and the unfamiliar (and even counterintuitive) concepts encountered in a chemistry course. They often do so without the same level of prior knowledge, familiarity, or confidence to successfully develop mastery within the pedagogical framework of traditional classrooms. Further, they may not have had the home experiences that support the internalization of academic discourse patterns that might be familiar to students from different backgrounds.[12] Okhee points out that ELLs rarely

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participated in national assessments (i.e., NAEP), and when they did, were not disaggregated from disabled student populations. Without being recognizable as a particularly high-need demographic, the tendency has been for ELLs to go largely unnoticed in conversations about STEM education reform. Not surprisingly, achievement gaps have been observed across subject areas and are likely to persist until classroom practices become aligned to the changing demographics of the student populations in our schools.[13,14]

Herein, we present a guided inquiry lesson that explored the relationship between the electronic structure of atoms and ions and their observable paramagnetic properties. The lesson was enacted at a high-needs high school in the Southeast within a class populated solely by ELL students.[15] Lesson design features that sought to support the ELL learners are outlined and discussed, and this discussion is followed by an analysis of student successes and challenges as they worked through the hands-on investigation and related assessment prompts. Lastly, the outcomes on a summative assessment are presented and discussed. These experiences are shared to inform an emerging conversation about teaching chemistry in culturally diverse classroom settings at the precollege level.

■ CLASSROOM CONTEXT

As noted earlier, the classroom where this lesson was implemented was composed of solely ELLs, and it was designed to support student growth in both chemistry content and English language skills. Students were taught using a collaborative teaching model involving an experienced science teacher with ELL certification and a student teacher in a chemistry teacher preparation program. This lesson was conducted about six months into a nine-month introductory course aligned to state standards based on the National Science Education Standards.[16] The class met across two periods and was attended by 19 students, all of whom were eligible for free or reduced lunch. All but one of the students came from a Hispanic background; the remaining student was of Asian heritage. The students in this class demonstrated a wide range of English-language ability, as some had been raised in dual-language families and were proficient at speaking English, while others came from non-English-speaking families and lagged behind in verbal ability. The class itself was structured such that group work featured prominently in the pedagogical approach, in the hope of providing opportunities for peer support. Specifically, students who struggled with language, but comprehended the material, were partnered with students who struggled with content, but comprehended the language, in a mutually beneficial arrangement. Students were encouraged to speak predominantly English to facilitate language development, but they would regularly revert to communicating in their primary language. These code-switching events most often occurred when instructions were not clear or when there were content questions that students were struggling to communicate in English.[17] More details regarding these observations will be presented in the Discussion section.

The aim of this lesson was to teach that electron configuration affects the properties of an atom or ion using an engaging but relatively uncommon (in the high school course) guided inquiry laboratory investigation adapted from a previous contribution in this *Journal*.[18] Additional details regarding the lesson can be found in the Supporting Information. Consistent with recommendations for supporting ELLs in learning science as outlined in the introduction, the inquiry-oriented activity was conducted within small collaborative groups and was designed to support the acquisition of language, science process skills, and fundamental conceptual understanding by considering the relationship between empirical outcomes and scientific explanations.

The class began in a whole-group setting to assess prior knowledge and to introduce the experimental setup. Students were first prompted to consider ideas about electron configuration and orbital filling from previous instruction by determining the electron configuration of a potassium atom and a potassium ion. From this instructional segment, it was observed that the students were generally familiar with basic aspects of atomic structure, writing and drawing out ground state electron configurations of atoms and ions, and a few common periodic trends. Next, while students were still in a whole-class setting, two questions were asked to ascertain their existing knowledge of magnetism. First, students were asked to define in their own words the term "magnetism" and then to explain in their own words by what source or means magnetism arises. After a short class discussion around these questions, the "magnetic salts" activity was introduced. The class was then split into two groups, one identified as needing a higher level of language support, which was under the instruction of the lead teacher, and the other requiring less language support, which was under the instruction of the collaborating student teacher.

Within each group, students worked in subgroups (as pairs) to develop predictions about the relative magnitude of influence a set of strong (neodymium) magnets might have on a vial containing various powdered, metallic salts (i.e., chlorides of Na^{+}, Mg^{2+}, Mn^{2+}, Fe^{2+}, Co^{2+}, Ni^{2+}, and Cu^{2+}). The composition of these subgroups was determined prior to the lesson such that each group would have a student who was proficient in the necessary content for the activity along with a student who had a strong grasp of English. Each subgroup was given a balance capable of reading to two decimal places, a rubber stopper, a set of four neodymium magnets, and vials that contained the salts. Students then worked in their subgroups to obtain data using a setup similar to that reported by Cortel.[18]

Once students obtained their data, the smaller lab groups were recombined into their original groups under the supervision of one of the coteachers. Students were prompted to identify any patterns in the data observed and develop an explanation for this trend. They were allowed several minutes to work on their explanations, at which point the explanations were shared out with the whole class. Both instructors provided support during the discussion through Socratic questioning and eliciting the contributions of other students.[19,20] During this "postlab" discussion, very little direct instruction was presented; instead, the emphasis was on student−student discourse, with some teacher-directed interventions to sharpen, refine, clarify, or assist in elaboration of student ideas.[21]

To assess the extent to which the instructional sequence, and particularly the small-group and whole-class discourse, promoted their understanding relative to the learning outcomes, the students were prompted to complete a written assessment of two open-ended questions. Question 1 asked students to explain how paramagnetism arises, while Question 2 focused on transfer by asking the student to compare the expected relative paramagnetism of two iron salts (one containing Fe^{2+} and the other Fe^{3+}).[22]

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J. Chem. Educ. XXXX, XXX, XXX−XXX

■ ASSESSMENT OUTCOMES

To evaluate the quality of responses, a three-level rubric was developed, ranging from "incorrect" through "partial" to "complete" (Table 1). Question 1 was categorized as complete if both features of paramagnetic properties (i.e., unpaired valence electrons and the presence of an external magnetic field) were included in the response, partial if either one but not both was included, and incorrect if neither was present. Six of the eight student responses were partially or completely correct, while the remaining two were incorrect.[23] Of the five partial responses, two of the students gave answers related to the presence of unpaired electrons, while the remaining three gave answers related to proximity to a magnetic field. Here is how one student explained paramagnetism (coded as complete):

Table 1. Summary of Assessment Outcomes for "Magnetic Salts" Activity

Assessment Prompt	Complete Response	Partial Response	Incorrect Response
Under what conditions can we observe paramagnetism? ($n = 8$)	1	5	2
How does the paramagnetism of $FeCl_2$ and $FeCl_3$ compare? ($n = 8$)	3	0	5

> *Paramagnetism will have an attractive force because you need to put them neour [sic] to a magnetic [sic] so they will be attractive because they have unpair [sic] electrons.*

Question 2 responses were classified as "complete" if both the appropriate ion (i.e., Fe^{3+}) and rationale (more unpaired electrons) were given; "partial" if the correct ion was chosen, but the reasoning was either absent or incorrect; and "incorrect" if neither the ion nor the appropriate rationale was given. Three responses were marked as complete, and five as incorrect. Of the five incorrect responses, three responses identified Fe^{2+} as the ion with stronger paramagnetic tendencies due to the fact that Fe^{2+} would have more electrons than Fe^{3+}. Here are two sample responses that were coded as incorrect and complete, respectively:

> *[incorrect]: The stronger effect on the balance is Fe^{2+} because it has 24 electrons.[complete]: It is Fe^{3+} because it is a paramagnet that will repulsive [sic] and it will have more unpaur [sic] electrons so it will be stronger.*

■ DISCUSSION

The outcomes from the formal written assessment indicated that the experience promoted some understanding concerning both the source and the relative magnitude of substances exhibiting paramagnetism. Additional support for this assertion arises from the observation that during the preactivity discussion it was evident that the students' knowledge of the ways in which "permanent" (i.e., ferromagnetic) magnetic substances generate a magnetic field was limited and that the phenomena of paramagnetism was completely unfamiliar. Further, since the primary focus of the lesson was to leverage a simple, engaging investigation that yielded unambiguous and consistent results with student argumentation to construct explanatory models that accounted for the results, it is less likely that students were simply verbalizing the correct answers on the assessment measures.[24−26]

It is not surprising, given the complexity of the phenomenon and the academic language needed to describe it, that the students' performance on the transfer item left room for improvement. A closer analysis of the subgroup's responses suggests that progress had been made toward achieving the content objectives. Three of the eight students had completely correct responses, which included identifying the correct ion, accounting for the reason that ion would have a greater effect on the balance, and providing a general explanation of paramagnetism. Three students had the correct description of the phenomenon of paramagnetism (e.g., "What causes paramagnetism is when its close to a magnet and gets an attractive force") but did not go further to provide an atomic-level explanation. By recognizing the challenges inherent in constructing such explanations,[27] it may be that these students struggled to identify the causal link or find the language needed for this step in the reasoning process and needed further scaffolding in this area. Finally, responses such as "Fe^{2+} is stronger because where [sic] only taking away 2 electrons but on the other where [sic] only taking one away" suggests that some of these students were still developing an understanding of foundational concepts needed to interpret this phenomenon.

There were other indicators of the potential value of using this approach in working with ELLs in chemistry classrooms. After watching classroom video of the lesson and considering the discourse structures in relation to concept development, an observation with potential implications to conceptual change research was made. Over the course of the activity, there were instances when students engaged in code switching; that is, there were segments of conversation in which they would communicate in English and others when they would talk to each other in Spanish. Through our analysis of the video, particular patterns emerged. At the beginning of the lesson, students spoke in English as the prior content was reviewed and the experiment explained. However, there was a noticeable shift over to Spanish that occurred during the data collection process as students conducted the experiment in their subgroups. Furthermore, when tasked to establish a scientific basis for the trend observed in their data, the dialogue between students took place predominantly in Spanish.[28] One explanation for these observations is that during times of low cognitive demand, such as when reading or explaining straightforward instructions, the majority of students could maintain a conversation in English. As the cognitive load of the task with which they were confronted increased, however, the effort required to switch their thoughts into another language (i.e., English) combined with the need to process experimental results and develop mental models that accounted for the data collected may have exceeded their working memory.[29] We hypothesized that the code switching that was observed during the more challenging aspects of the lesson was done to reduce the cognitive demand by eliminating the extra processing skills required to translate their ideas from their native language into English and vice versa.[30]

In this vein, Collison found that far higher cognitive level statements were made in their native language than in English by Ghanaian children during science class discussions.[31]

The importance of this observation is two-fold. First, an observant teacher could analyze the language being used by their students as a metric to gauge the cognitive load being placed on them. In classrooms where only native English speakers are present, it may be difficult to determine at which points of the lesson students are being faced with conceptual challenges that place a high demand on their working memory since they will still be speaking in English. In ELL-inclusive environments, however, the non-native speakers' code switch-

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J. Chem. Educ. XXXX, XXX, XXX−XXX

ing can cue the teacher to provide additional linguistic or other support to facilitate the learning of all students.

Second, for this proposed pedagogical strategy to be effective, it must take place within the appropriate activity structure.[30,32] Having an engaging activity in which students are willing to exert the mental energy required to make sense of a phenomenon is critical. Utilizing an inquiry-based approach has value because it provides a less constrained environment than direct instruction in which students can play with language and play with ideas. Balancing that freedom, though, with the structure of *guided* inquiry makes it possible for students to focus on the explanatory mechanisms and the underlying principles of a phenomenon instead of exerting energy developing their own experimental design. While it was not used in this lesson, the insight about the timing of code switching suggests that further support could be given to students by establishing structured code-switching routines in the activity structure.[33] For instance, students could be encouraged to use English during parts of the lesson activity during which less cognitively demanding thinking is required (e.g., proposing initial ideas, completing the procedure) and encouraged to use their native language when more cognitively demanding thinking is necessary (e.g., in constructing initial explanations).

As was employed in this lesson, there may exist benefits of creating groups that mix students with high conceptual ability with students with high language ability. Such a pairing allows the student with a strong grasp of the English language to translate information and instructions presented to a student with conceptual understanding but a limited grasp of the language. By allowing students to engage in dialogues throughout the activity, ELLs are allowed to utilize their native language strengths to deepen the experience. Over the course of the activity, there was extensive dialogue between the students. Rollnick and Rutherford found that the students' use of native language during science investigations promoted more thorough exploration of the phenomena and greater propensity to communicate different ideas, including alternative conceptions.[34] Once ideas are developed in the students' native language as necessary, students should be required to present explanations and formalize understandings in English to support development of academic vocabulary.

Reflection on the lesson by the authors suggested future modifications in the enactment of similar learning experiences that would both better marshal the code switching and help students more fully acquire competence in academic vocabulary in English. It was noted that when students were working through the activity's guiding questions, they often used primarily Spanish. As the activity structure shifted to sharing out their explanations, first in the subgroups and then as a whole class, students would try to explain in English (as this was a course requirement), and then when they got stuck, they would revert to Spanish until someone (usually a classmate) helped them find the way to communicate their thoughts in English. A missing piece in the enactment of this lesson was that once an acceptable scientific explanation had been developed, the work stopped. It would likely be more effective to put students in pairs following the development of this consensus explanation and have them re-explain it to each other solely in English. Finally, once the pairs all felt confident in their ability to complete this English-only verbalization, then students should have been asked to write their understanding of the phenomenon in English, perhaps using the claims–evidence–reasoning framework.[35] Adding this additional piece to the instructional sequence would likely have improved the students' performance on the post assessments.

One limitation of verifying the efficacy of this suggested activity is the small sample size. Future endeavors that utilize the same or similar activity, with and without supporting activities or models, would be beneficial in ascertaining a better instructional sequence as well as determining the minimum number of activities required to guarantee mastery of these concepts. For instance, it would also be useful to see if this activity would be better utilized at the beginning of a unit on electron configuration instead of being placed at the end. Lastly, it would be useful to apply this same study to ELL students in an inclusive (i.e., both native and non-native speakers) environment to better draw comparisons between the two different modes employed to teach ELL students.[36]

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/ed500837p.

Learning outcomes; ordering information for necessary materials; instructor notes (PDF, DOCX)

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Notes

The authors declare no competing financial interest.

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