The Impact of Nanoscience Context on Multiple Choice Chemistry Items

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Abstract
Modern chemistry topics are often introduced into classrooms long before they appear in standardized exams. This paper investigates the role of a nanoscience context in multiple choice items by using a comparative description of the cognitive load effects of such items on a practice exam that was given to students in 2nd semester general chemistry and 1-semester pre-engineering general chemistry. It includes a classroom comparison study of performance and mental effort analyses in twelve chemistry content areas including a nanoscience and materials context category. In addition, cognitive load effects of paired items in four subcategories were evaluated. Results from the study shed light on the cognitive load effects of nanoscience and materials exam items when these contexts are included within the undergraduate general chemistry classroom.

Disciplines
Curriculum and Instruction | Educational Assessment, Evaluation, and Research | Higher Education | Other Chemistry | Science and Mathematics Education

Comments
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The Impact of Nanoscience Context on Multiple Choice Chemistry Items

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Modern chemistry topics are often introduced into classrooms long before they appear in standardized exams. This paper investigates the role of a nanoscience context in multiple choice items by using a comparative description of the cognitive load effects of such items on a practice exam that was given to students in 2nd-semester general chemistry and 1-semester pre-engineering general chemistry. It includes a classroom comparison study of performance and mental effort analyses in twelve chemistry content areas including a nanoscience and materials context category. In addition, cognitive load effects of paired items in four subcategories were evaluated. Results from the study shed light on the cognitive load effects of nanoscience and materials exam items when these contexts are included within the undergraduate general chemistry classroom.

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Introduction

The emphasis for including novel arenas of technological advancement including nanotechnology and green chemistry within the chemistry classroom...
has been fueled primarily by society’s call for more future innovators to propose global solutions to environmental, medical and engineering issues that have long continued to peril society. To encourage research and development in the field of nanotechnology, the U.S. government established the National Nanotechnology Initiative (NNI) in 2001, whose annual budget has nearly tripled since its inception (1).

The option of including nanoscience within an individual course essentially lies within the purview of the instructor, but there are hurdles to that inclusion on a large scale, including such things as nationally normed exams. In chemistry, such exams have been produced for over 70 years by the Examinations Institute of the Division of Chemical Education of the American Chemical Society. National exams invariably reflect a conservative assessment of content coverage, so new material, such as nanoscience, is often slow to appear. In principle, it is easier to include new content by providing context for “traditional” coverage rather than testing content that is specific to the emerging field – in this case nanoscience. In order to carry out such context based inclusion, however, it is important to understand the impact of the context, and the study reported here investigates this question utilizing a novel analysis based on cognitive load theory. To date, no other published work exists in the literature which involves the use of nanoscience and special materials assessment items to examine the cognitive implications of various chemistry classrooms with respect to their inclusion or omission of these learning contexts.

Cognitive load theory may be described as the amount of mental activity imposed on the working memory at any instance in time. This concept is arguably descendent from the seminal paper by Miller in 1956 (2) which proposed that the human cognitive system can actively process \(7 \pm 2\) pieces of information at any time. While direct measures of cognitive load are a challenge, the studies of Gopher and Braun (1984) indicated that “subjects can subjectively evaluate their cognitive processes, and have no difficulty in assigning numerical values to the imposed mental workload or the invested mental effort in a task (3)” (4, p. 739). Although mental effort has been measured using various techniques (5, 6), including: rating scales, physiological techniques (i.e. heart-rate variability and pupil dilation response (7), and dual-task methods), subjective measures have been found to be very reliable, unobtrusive and very sensitive (8-11). “The intensity of effort expended by students is often considered the essence of cognitive load (12, 8)” (10, p. 420), and most studies for measuring mental effort have used a subjective rating system (13).

Combined measures of performance and mental effort can be used as a tool to help us learn more about instructional efficiency (4). In our previous work (14), we established a method for determining cognitive efficiency in different chemistry categories using a combination of performance and mental effort measures collected from three large general chemistry classrooms who took a practice exam. In this paper, we present the results of a synonomous research study that was carried out in conjunction with our cognitive efficiency analysis, where we investigated the cognitive load impacts of nanoscience context on multiple-choice exam items for “standard” general chemistry and pre-engineering general chemistry students. Results from this study provide...
new insight into the cognitive load consequences of nanoscience context on test items when students are introduced to such topics in their chemistry classrooms.

**Instrument Design**

The practice exam instrument used in our study utilizes 50 multiple choice items, including 6 items specifically keyed to materials science and/or nanoscience. After each exam item, a mental effort item was inserted into the exam format that asked students to introspect on the degree of mental effort expended on the previous question answered (Figure 1). We used a 5-point Likert scale consistent with the number of available multiple choice options found on a typical scantron answer key.

```
How much mental effort did you expend on question #1
- Very little
- Little
- Moderate amounts
- Large amounts
- Very large amounts
```

*Figure 1. Example of mental effort item inserted into the practice exam format.*

Two nanoscience items in the sub-categories of spectroscopy and band theory, as well as two materials items in the sub-categories of intermolecular forces (IMF) and Lewis structures, were inserted into the practice exam to serve as paired items to non-nanoscience/materials items on the exam in the same sub-categories.

**Exam Administration**

The practice exam was given approximately one week prior to final examinations in courses at an urban university in the Midwest. Data described here arises from performances from a total of 158 students who took the practice exam (83 students in 2nd-semester general chemistry and 75 students in the single-semester pre-engineering chemistry course) and further agreed to participate in the research component of the study by signing the relevant IRB consent form. Students received individualized email feedback within one day of taking the practice, which included both their performance and mental effort averages in twelve chemistry content areas including the nanoscience and materials content area. Aside from research purposes, the information provided from the practice exam was primarily meant to help students validate their current levels of content knowledge, cognitive resource usage, and potentially guide them in developing a better study plan to prepare for their upcoming final exam the following week.
Data Analysis

Cognitive efficiency analysis, as described in our previous work (14) allowed us to probe differential performance and mental effort effects for all items on the practice exam, including the nanoscience and materials science items for the two different types of general chemistry courses (Figures 2 & 3).

When comparing the cognitive efficiency graphs (Figures 2 & 3) for the two different types of chemistry courses (2nd-semester general chemistry vs. 1-semester pre-engineering survey course), individual differences in terms of the relationship between performance and utilization of mental resources in different chemistry areas can more clearly be identified. Both courses (2nd-semester general chemistry and single-semester pre-engineering chemistry) show low cognitive efficiency in the solutions category, an observation that may be important for instructors because it is apparently robust regardless of the course emphasis or instructor. Given the different emphasis of the course and time for instruction, comparisons between the one-semester course for engineering students and the traditional two-semester general chemistry sequence courses provides additional observations. First, the high cognitive efficiency in the nanoscience and materials chemistry area for the single-semester pre-engineering chemistry course is achieved despite the “survey”

![Graph of cognitive efficiency in different chemistry categories for 1-semester pre-engineering chemistry course. Normalized values (a.k.a. standardized or “z scores”) for classroom performance in each chemistry category are plotted against normalized values for average mental effort in each category. Values in the upper left quadrant indicate content areas of high performance and low mental effort, values in the upper right quadrant indicate content areas of high performance and high mental effort, values in the bottom left quadrant indicate areas of low performance and low mental effort, and lastly, values in the lower right quadrant of the graph indicate areas of low performance and high mental effort.](image-url)
nature of this course. This observation supports the establishment of a hypothesis that introduction of modern concepts into general chemistry such as nanoscience and materials may prove effective even if the time invested is modest (no topics receive large allocations of time in the one-semester survey course).

![Graph of cognitive efficiency in different chemistry categories for 2nd-semester general chemistry students](image)

**Figure 3.** Graph of cognitive efficiency in different chemistry categories for 2nd-semester general chemistry students (average of two 2nd-semester general chemistry course sections).

**Paired Item Analysis**

The second component of analysis for determining the cognitive load effects of nanoscience and materials science contexts on exam items for the two different chemistry courses, involved a paired item analysis. Two nanoscience items in the sub-categories of spectroscopy and band theory, as well as two materials items in the sub-categories of intermolecular forces (IMF) and Lewis structures, were inserted into the practice exam to serve as paired items in these same sub-categories. The first comparison we analyzed was both groups of students’ differential performance on non-nanoscience and materials exam items versus nanoscience and materials items (Figures 4 & 5).

In Figure 4, the performance comparison on non-nanoscience and materials & nanoscience and materials items for pre-engineering chemistry students, it can be seen that in both the areas of spectroscopy and Lewis structure, the engineering students have a higher performance when the format of the item includes reference to either nanoscience or special materials. This observation is very interesting, because unlike the areas of intermolecular forces and band theory, neither of these concepts were known to be taught in the context of
Figure 4. Performance comparison on non-nanoscience and materials (grey) and nanoscience and materials (black) exam items (1-semester pre-engineering chemistry students).

nanoscience or materials (either during the lecture component or textbook contents).

In Figure 5, the performance comparison on paired items for 2nd-semester general chemistry students, it can be seen that in all four areas the students perform better when the items are not presented within the context of nanoscience or materials.

The discrepancies found between performances of 2nd-semester general chemistry students and pre-engineering chemistry students on contextualized exam items suggest something about the role various learning environments will play on the performance of students on these particular items. Although content coverage in the two general chemistry courses was similar, four things were notably different, (1) different instructors taught the courses; (2) the single-semester pre-engineering course was a survey course with engineering applications; (3) it did not cover the traditional chemistry content in as much depth as two semesters of general chemistry; and (4) the textbook used for the pre-engineering general chemistry course included nanoscience and materials context. Regardless of these differences between the two courses, the pre-engineering general chemistry students were not introduced to the concepts of spectroscopy and Lewis structures within the context of either the nanoscience or materials. Furthermore, these results hint at the possibility that a greater transfer of knowledge in these chemistry areas was achieved due to the nanoscience and materials contextual emphasis inherent in the pre-engineering chemistry course in comparison to the regular general chemistry course.

The practice test instrument also allows a comparison of student perceived mental effort as shown in Figures 6 and 7.
The average mental effort comparisons in Figures 6 and 7, indicate differential cognitive load effects experienced by the two different groups of students (1-semester pre-engineering chemistry students versus 2nd-semester general chemistry students) on paired items.

**Figure 5.** Performance comparison on non-nanoscience and materials (grey) and nanoscience and materials (black) exam items (2nd-semester general chemistry students).

**Figure 6.** Average mental effort comparison on non-nanoscience and materials and nanoscience and materials exam items (1-semester pre-engineering chemistry students).
For the area of intermolecular forces, both groups of students perceived the nanoscience materials item to be more mentally challenging. For the area of band theory, the 2nd-semester general chemistry students perceived the nanoscience and materials item to be substantially more mentally challenging than the pre-engineering general chemistry students. This result is not surprising as band theory is a topic which is more heavily emphasized in the pre-engineering general chemistry course than in other general chemistry courses. For the area of spectroscopy, the 2nd-semester general chemistry students indicated that they exerted less mental effort when attending to the nanoscience and materials item (average mental effort of 2.4 item) than the paired item (average mental effort of 3.0). The most interesting aspects of the results from the spectroscopy paired items is that although the pre-engineering chemistry students experienced a negligible difference in cognitive load for the paired spectroscopy items, they performed substantially better than the 2nd-semester non-engineering general chemistry students on the nanoscience and materials item. Again, the chemistry concept of spectroscopy was not taught in either the context of nanoscience or materials in the pre-engineering course. This result bolsters the suggestion that the pre-engineering chemistry students may have experienced improved transfer test performance gain for the topic of spectroscopy over the 2nd-semester general chemistry students due to the general inclusion of this context elsewhere in the course.

![Average Mental Effort Comparison on Non-nanoscience/Spec Materials & Nanoscience/Spec Materials Items](image)

**Figure 7.** Average mental effort comparison on non-nanoscience and materials and nanoscience and materials exam items (2nd-semester general chemistry students).

In the last area, Lewis structures, the average mental effort data allows us to explore the differential cognitive load effects of the Lewis structure paired items. The pre-engineering students appear to be exerting less mental effort for the nanoscience and materials Lewis structure item relative to the paired item.
For the 2nd-semester general chemistry student, the cognitive load effects of the Lewis structure paired items are quite comparable.

**Conclusion**

This paper investigates the performance and cognitive load effects of nanoscience and materials exam items for 1-semester pre-engineering students and 2nd-semester general chemistry students. The performance and mental effort histograms and cognitive efficiency analyses confirmed that students in the 1-semester pre-engineering chemistry course who are exposed to nanoscience and materials context in both their classroom and textbook material, in general have both higher performance and greater cognitive efficiency in this area.

Performance and cognitive load effects of paired items in four subcategories (intermolecular forces, band theory, spectroscopy, and Lewis structures) were evaluated and compared for 1-semester pre-engineering students and 2nd-semester general chemistry students. Evidence from these studies suggest that for a course where students have some contextualization utilizing nanoscience, no differences arise when the exam items contained nanoscience and materials context. In contrast, for a course that does not include any nanoscience contextualization students performed much better on the non-nanoscience items than nanoscience and materials items. The average mental effort (a.k.a cognitive load data) from the paired items indicated that nanoscience and materials items imposed the same amount of cognitive load as the non-nanoscience and materials item for the pre-engineering students. For the 2nd-semester general chemistry students, on average, the cognitive load differences of nanoscience and materials items and non-nanoscience and materials items (for these 8 items on the practice exam) were minimal. Furthermore, the nanoscience and materials items that were included on the practice exam used in our study, did not impose differential cognitive load effects on one population of students over another. These results suggest that although including nanoscience and materials items on multiple choice exams may put students who have been exposed to the nanoscience context at some level in the classroom (either through classroom discussions or integration in the textbook) at a slight advantage, these items on average do not impose additional cognitive load for regular general chemistry over students in a 1-semester pre-engineering chemistry survey course.

These results, for a limited set of nanoscience context items, suggest that the addition of nanoscience to national exams can be accomplished. It is, however, likely important that instructors look to include nanoscience context in their courses. Even when the inclusion of nanoscience is not directly related to the topic tested, exposure to the idea appears to help students in terms of both exposure and mental effort.
Suggestions to Instructors

There are a number of methods a chemistry instructor can use to begin to incorporate non-traditional context such as nanoscience, special materials and green chemistry content into their classrooms. Such methods include incorporation of textbook and/or laboratory manual material, on-line resource information (i.e., of which several excellent examples exist) and may include such things as general information, animations, teaching modules, laboratory modules, use of remotely accessible instrumentation for studying such materials, and even outreach activities. Of course, students are always welcome and can be invited by chemical educators to further entertain their own curiosities of such topics through use of these resources as well. A list of some of the available resources for inclusion of nanoscience and materials context in the chemistry classroom can be found below.

Books (some of which may have accompanying lab manuals):

Chemistry for Engineering Students by Lawrence Brown (Author) and Thomas Holme (Author)

Tomorrow's Chemistry Today: Concepts in Nanoscience, Organic Materials and Environmental Chemistry by Bruno Pignataro (Editor)

Single Molecule Chemistry and Physics: An Introduction (NanoScience and Technology) by C. Wang (Author) and C. Bai (Author)

Introduction to Materials Chemistry by Henry R. Allcock (Author)

Functional Molecular Nanostructures (Topics in Current Chemistry) by A Dieter Schliter (Editor)

Introduction to Nanoscience by Gabor L Hornyak (Author), H.F. Tibbals (Author), J. Dutta (Author), and A. Rao (Author)

Nanochemistry by G.B. Sergeev (Author)

NanoBioTechnology: Biolnspired Devices and Materials of the Future by Oded Shoseyov (Editor) and Ilan Levy (Editor)

Nanoscale Materials in Chemistry by Kenneth J. Klabunde (Editor)
On-line resources:

http://invsee.asu.edu/Invsee/invsee.htm
IN-VSEE Interactive Nanovisualization in Science & Engineering Education web-site

http://mrsec.wisc.edu/Edetc/
Materials Research Science and Engineering Center on Nanostructured Interfaces

http://www.nanoed.org/index.shtml
NanoEd Resource Portal

http://www.cns.cornell.edu/index.html
Center for Nanoscale Systems

http://www.nnin.org/nnin_edu.html
National Nanotechnology Infrastructure Network Education Portal

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