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Isabelle D. Cherney
Creighton University, cherneyi@creighton.edu

Jordan Winter
Creighton University

Michael G. Cherney
Creighton University

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**NUCLEAR PHYSICS PROBLEM SOLVING:
A CASE STUDY OF EXPERT-NOVICE DIFFERENCES**

Isabelle D. Cherney and Jordan Winter

Department of Psychology
Creighton University
2500 California Plaza
Omaha, Nebraska 68178
cherneyi@creighton.edu

and

Michael G. Cherney

Department of Physics
Creighton University
2500 California Plaza
Omaha, Nebraska 68178

ABSTRACT

We examined problem-solving in nuclear science by gifted junior high school students, senior high school students, first year undergraduates, undergraduate physics majors, and graduate teaching assistants. The first study examined differences between “expert” and “novice” approaches, whereas the second study investigated the learning of problem-solving skills with a pre- and post-test. The results showed that with increased experience or expertise, students tended to solve the problems using higher levels of Bloom’s (1956) taxonomy. Junior high school students’ performance improved significantly after a week-long hands-on nuclear physics class. However, when solving a more conceptual nuclear physics problem, there were no significant differences in the pre- and post-tests of the gifted students at the same grade level. These studies suggest that gifted junior high school students have comparable cognitive abilities to older students, but that they lack the necessary knowledge base, that they use problem solving strategies that are “lower” on Bloom’s taxonomy, and that they focus on memorization rather than methods which are evaluative or synthetic.

† † †

In the United States, relatively few students take science classes during their junior high school years, although, as Piaget would suggest, young adolescents have the cognitive abilities to master the classes. Piaget (1977) theorized that cognitive development proceeded in four qualitatively different stages. The last stage, formal operations, is typically reached after about the

age of 11. During this stage adolescents’ thinking becomes abstract and symbolic and they develop reasoning skills and a sense of hypothetical concepts (Piaget 1977). Thus, junior high school students should have the same cognitive abilities as older students, but they are lacking experience. Experience and knowledge greatly enhance problem solving abilities and account for differences between experts and novices (Chi et al. 1982).

Problem solving involves at least three dimensions: (a) domain knowledge, (b) problem-solving methods, and (c) characteristics of problem solvers (Ronning et al. 1984). First, rich domain knowledge (knowledge schema) allows experts to classify problems more readily and thus guide their solutions in a more efficient and skilled way (e.g., Larkin et al. 1980). Because novices tend to lack such a developed schema, they are more likely to search in an undirected fashion for a solution. Second, evidence suggests that junior high school students do not profit from a general problem-solving strategy (Ronning et al. 1984). Rather, they may benefit more from a hands-on approach to teaching science. Good problem solvers tend to gain from personal experience and general knowledge, from being able to use analogies, and from metacognitive skills.

Most educators hope to impart knowledge that can be applied to situations other than those that were directly taught. This objective is tempered by persis-

tent results of studies showing that experience with particular problems often yields little or no transfer to similar problems (e.g., Gick and Holyoak 1980). Transfer across different contents is facilitated by stressing crucial aspects of the learned problem that might be useful in other situations (Bassok 1990) and by giving students problems without solutions which force them to focus on new aspects of the problem (Adey and Shayer 1990).

Successful physics students are those students who understand complex physics formulas in basic terms (Sherin 2001). Understanding the fundamental building blocks of physics and being able to transfer them to understand complex formulas permits students to gain the understanding and flexibility necessary for transference of knowledge to other problems in physics. Research on Newtonian mechanics problem solving suggests that undergraduate students can be adept at solving traditional quantitative physics problems while still having an extremely poor conceptual or qualitative understanding of the principles involved (Halloun and Hestenes 1985).

The purpose of the first study was to identify, compare, and depict the expert and novice problem-solving styles of gifted junior high students, senior high students, undergraduates, undergraduate physics majors, and graduate teaching assistants solving a nuclear physics problem. Problems in nuclear physics were chosen because the topic is less familiar to introductory students and thus unfamiliarity may control for possible differences in existing knowledge base among these students.

It was hypothesized that students who had accumulated more expertise in the sciences would use different problem-solving skills than those who had fewer science classes (Chi et al. 1982). Using Benjamin Bloom's (1956) taxonomy to categorize levels of abstractions, we expected that junior high school students would solve the physics problems using lower levels of the taxonomy than the undergraduate and graduate students.

STUDY 1

METHOD

Participants

A total of 38 gifted junior high school students, 21 senior high school students, 188 undergraduate students (enrolled in different physics classes: Astronomy, first (I) and second (II) semesters of General Physics), 7 undergraduate physics majors and 10 teaching assistants participated. The gifted junior high and senior

high school students participated while completing a one-week summer course in nuclear physics. The one-week course was open to seventh and eighth grade students who were identified as gifted by their school. The undergraduate and graduate students were students enrolled in courses at a private Midwestern university. The majority of the participants were European-American.

Procedure

Undergraduate students enrolled in a physics course and gifted junior high and senior high school students attending a one-week summer program were given a nuclear physics problem at the beginning of the first class. In an effort to identify possible misconceptions due to their exposure to and familiarity with other sciences, the students were asked to identify what science classes they had previously taken. Participants were given the following nuclear physics question: "Radon is a radioactive gas. It occurs naturally and seeps out of the earth's crust. The gas can find its way into buildings through cracks in basement floors and walls. About half of the effective radiation dose we receive is related to breathing in radon gas. Radon has a half-life of about 2 days. Imagine a sample of radon gas that is kept in a sealed bottle. Estimate how much of the original radon will remain after 5 days. Show how you calculated your answer. Do not use a calculator." In addition, four sub-questions pertaining to the problem were also on the questionnaire: (a) "Explain the term "half-life" using your own words, (b) How does radioactivity like we see in Radon decay occur? Describe this in terms of what goes on in the atomic nucleus, (c) What determines which radon nuclei decay when? and (d) What are the products of this decay and what happens to them?" Participants were given as much as time as they needed to answer the questions.

Coding

All responses were read and coded independently by two trained experimenters using Bloom's (1956) 6-point taxonomy and was categorized into three levels of problem-solving (i.e., "Identification" corresponded to levels 1 (knowledge) or 2 (comprehension) of the taxonomy, "Application" corresponded to levels 3 (application) or 4 (analysis), "Generalization" corresponded to levels 5 (synthesis) or 6 (evaluation). Inter-rater reliability was 85%. Responses were also coded for correctness, use of graphs in solving the problem, and previous science experience.

RESULTS

Three levels of problem solving ability were identified: (a) ability to identify a workable method (Bloom's levels 1 and 2), (b) ability to apply the method (levels 3 and 4), and (c) the ability to generalize the method

Table 1. Levels of problem solving ability (Study 1).

Level	Identification (Bloom level ≥ 1)	Application (Bloom level ≥ 3)	Generalization (Bloom level ≥ 5)
Junior High	17%	12%	5%
Senior High	52%	38%	19%
Undergraduates	70%	51%	38%
Graduates	91%	82%	41%

(levels 5 and 6). Table 1 shows the percentages with which students from the different class groupings demonstrated these abilities. In general, the gifted junior high school students solved the physics problem using lower levels of Bloom's taxonomy than high-school students, the students in both general physics classes and the teaching assistants.

STUDY 2

The purpose of the second study was to identify the possible transfer of strategies learned during a short intensive summer education program. Thus, the second study compared gifted students participating in a week long intensive 9-hour physics class to the performance of undergraduates in the same situation. The students were given pre- and post-tests in two nuclear physics problems: the same problem as in Study 1, this time including a short text example, and a nuclear physics problem that requires the use of synthesis to obtain a solution.

METHOD

Participants

For the second study, a total of 59 gifted junior high school students (42 males and 17 females) and 49 undergraduate students (24 males and 29 females) from an introductory Astronomy class attending classes from the same private Midwestern university as in Study 1 participated. The majority of the students were of European-American descent.

Procedure

Participants were provided with the same question as in study 1 with an added introductory text: "The number of particles emitted in a given length of time by a sample of a radioactive isotope equals a definite percentage of the number of atoms in the sample. For example, in any sample of ^{11}C , 3.5 percent of the atoms break down each minute. At the end of a minute only 96.5 % will remain. At the end of 2 minutes about

96.5% of this amount or 93.1 % of the original amount, will remain. At the end of 20 minutes, only half of the original quantity will remain. This shows the half-life of ^{11}C is 20 minutes." In addition, students were instructed to complete a second nuclear physics question on cosmic rays. The introductory text was as follows: "Cosmic rays are particles of high energy that originate in outer space. Many can penetrate thousands of feet of rock. The rays from radium, nuclear bombs, or X-ray machines can penetrate only a few inches of lead." The question stated: "It is observed that most cosmic rays which are detected at the surface of the earth come from above, a few come from the side, and almost none come up from the earth. Try to offer an explanation as to why we see more cosmic rays coming from directly above and fewer coming from other parts of the sky." The questionnaire was given on the first and last day of 3 one-week summer education programs for junior high school students and on the first and last day of the corresponding instruction in an introductory astronomy college class.

Coding

Similar to Study 1, responses were coded by two trained independent experimenters using Bloom's (1956) taxonomy (i. e., no meaningful answer = 0, knowledge = 1, comprehension = 2, application = 3, analysis = 4, synthesis = 5, and evaluation = 6) and for the students' levels of problem-solving (e.g., operations without knowledge, recognition of what half-life is, answer with or without an explanation, correct or incorrect work). Inter-rater reliability was 85%.

RESULTS

Question number 1

Because not all students completed both pre- and post-tests, the data for 53 junior high school students and 47 undergraduate students were used for data analyses. Overall, a total of 16 junior high school students (30%) and 12 undergraduate students (26%) responded correctly to the first question.

A paired *t*-test on the total pre- and post-test taxonomy with separate analyses for each group revealed that, on the pre-test junior high school students had an average taxonomy score of 1.96 ($SD = 1.16$) and an average taxonomy score of 3.13 ($SD = 1.27$) on the post-test $t(54) = -3.70, p = .001$. Undergraduate students had an average pre-test taxonomy score of 3.29 ($SD = 1.34$) and a post-test score of 3.03 ($SD = 1.24$). An independent *t*-test on the difference scores (post-test – pre-test) between the junior high and undergraduate samples revealed that the improvement between the pre- and post-tests was due to the significant improvement in taxonomy scores of the junior high school students, $t(84) = 2.81, p = .006$. On average, their taxonomy level scores increased by 1.17 points, whereas the change in the undergraduate taxonomy scores was not statistically significant. The pre- and post-test mean taxonomy scores for the junior high students and undergraduate students are shown in Figure 1.

Similar to the first study, three levels of problem solving ability for the junior high school students were identified: (a) ability to identify a workable method, (b) ability to apply the method, and (c) ability to generalize the method. Students were given a mathematical method of problem solving in the reading. In their laboratory experience they were given a graphical

method. Table 2 displays the percentage of junior high school students who achieved a particular level of problem-solving ability as a function of their exposure to problem-solving methods. It should be noted that although the students were given training in a graphical method, they chose to use mathematical solutions.

In terms of gender, an independent *t*-test on the taxonomy difference scores (post-test – pre-test taxonomy scores) showed no significant gender differences, $t(84) = .34, ns$.

Question number 2

Again, the data are based on the responses of 53 junior high school and 47 undergraduate students. Similarities in responses were found between gifted junior high students and college undergraduates. Only 7 junior high school students and 7 undergraduate students correctly answered the pre- and post-test question.

The second problem is more complex requiring two pieces of understanding. (Cosmic rays absorption is related to the amount of material traversed and the amount of material traversed is less for a particle reaching an observer on the earth's surface if it comes from directly above than if it enters at the horizon.) The students who answered incorrectly in each group gave

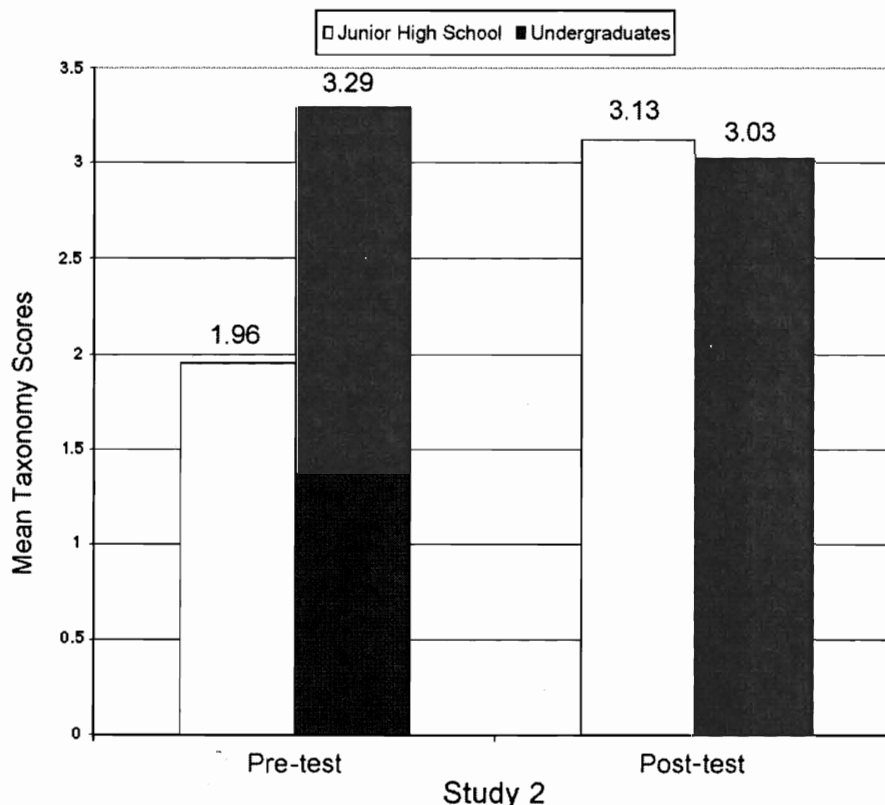


Figure 1. Pre- and post-test mean taxonomy scores for junior high and undergraduate students in Study 2.

Table 2. Problem solving ability as a function of level of problem-solving instruction for the gifted junior high school students for Study 2.

Level	Identification (Bloom level ≥ 1)	Application (Bloom level ≥ 3)	Generalization (Bloom level ≥ 5)
None (S1 pre-test)	17%	12%	5%
Reading (S2 pre-test)	65%	34%	15%
Laboratory (S2 post-test)	80%	48%	31%

similar wrong explanations (gravity, magnetism, reflected rays, and various tautologies). No change was observed in the number of students in either group who answered the question correctly.

GENERAL DISCUSSION

The present studies were designed to examine problem-solving skills in nuclear physics in gifted junior high school, senior high school, and undergraduate students. The current studies consisted of assessing three different groups: (a) students with a pre-test only (Study 1), (b) students with the same pre-test but with the inclusion of an additional introductory paragraph (Study 2 pre-test), and (c) students who attended intensive physics instruction (Study 2 post-test). Similarity between gifted junior high school student performances to that of college-bound high school seniors on standardized tests suggests similar academic potential (Hsu 2003). Overall, responses to questions on nuclear science (an area where students are likely to have at best a limited exposure) of gifted junior high school students and college undergraduates showed comparable content retention and reasoning ability.

The findings of the first study supported the hypothesis that students with more experience in problem-solving (or school years) are more likely to utilize higher cognitive processing (as per Bloom's (1956) taxonomy) to solve nuclear physics problems than younger students. That is, junior high school students were on average less likely to use higher levels of Bloom's taxonomy than undergraduate (in their first or second semester of general physics) or graduate students. Younger students tend to lack the experience and knowledge that is necessary to solve complex problems. We have summarized the characteristics of novice and experts taken from various cited sources in Table 3. The difference between expert and novice problem solving lies in the additional step experts take, moving from the problem statement to a qualitative analysis of the problem to end up with the critical equation. In contrast, novice problem solvers will tend to move from the

problem statement directly to the equation. In our studies, the gifted junior high students' taxonomy scores were similar to those of the introductory astronomy students, suggesting that both groups of students solved the problems at a similar level of abstraction. It should be noted that undergraduates with little science background tend to enroll in the astronomy class.

The results of the second study showed that gifted junior high students exhibited similar problem solving abilities to undergraduate students after having attended a week-long hands-on nuclear physics class. This improvement may be due to the experience the junior high school students received over the one-week laboratory experience. Taken together, the studies

Table 3. Expert and novice problem-solving

Experts

- Have models/schemas of problem situations in memory
- Focus on "essential information"
- Tend to use "physical representations"
- Tend to organize subject-matter knowledge (equations, definitions, procedures) hierarchically under fundamental concepts such as Newton's second law
- Have a rich knowledge of the domain which allows to plan ahead, to think forward

Novices

- Often have not encoded their experiences well, making retrieval at appropriate times difficult
- Have trouble mapping
- Lack relevant/personal experiences
- Possess models of problem situation in memory
- Tend to use means-end analyses and work backward
- Tend to organize subject-matter knowledge based on surface features rather than underlying conceptual frameworks

confirm that junior high school students have the ability to solve complex physics problems (e.g., Piaget 1977), although they may lack relevant experiences and tend to focus on surface features rather than underlying conceptual frameworks (Chi et al. 1988).

The differences between expert and novice problem solving were also manifest in the students' answers. With increasing expertise, students were more likely to correctly describe the meaning of "half-life." They were also more likely to apply the concepts, and to generalize their knowledge to another problem space. In Tables 3 and 4, we have summarized the characteristics of novice and expert problem solving which appear in the literature and are consistent with our observations. Although the junior high students were able to solve the physics problem, they were likely to use information they had previously memorized.

The responses to the second problem of Study 2 showed that almost no students were able to change their answer from incorrect to correct following a set of laboratory exercises, even though these showed the absorption of radiation as a function of material traversed. Along with the lab, students were given a set of lectures, one of which included an explanation of why the sun is red at sunset (more absorption of visible light due to a longer atmospheric path length). This cosmic ray problem, rather than testing simply operational understanding, demanded a synthesis to obtain a correct solution. Some students did recognize the question was related to one of the topics discussed, but only two middle schools students were able to put the two pieces together and formulate a new correct answer. It should also be noted that two other middle school students changed their answer from a correct response to an incorrect response. The connection between two seemingly independent pieces of information, one involving

cosmic rays and the other involving visible light was not clear to the students involved. Based on student responses we were not able to identify if the inability to come to a correct solution was the result of ineffective pedagogy related to one or both of the relevant topics or if the synthetic process is not part of the tool set that students bring to problem solving in this type of academic setting.

Transference from previous science courses is an important factor in problem-solving. The results showed that those who answered the questions correctly were more likely to have completed several high school science classes than those who answered the questions incorrectly. Future research should focus on which pedagogical tools provide the most helpful model(s) for the students to develop a correct approach of a question.

The extent of the contributions general science ability, mathematical ability, and verbal ability have on each other has gained attention. Although links between these factors have been found, standard tests used to measure these abilities often do not measure the effect they have on each other so no firm conclusions can be made (Lynch 1992). Previous studies also suggest that motivation and self perception models are important factors in problem-solving. Ziegler and Heller (2000) found that high motivation often accompanies higher self-concepts of competence and lower levels of helplessness. The interaction between talent, motivation, and confidence in achievement must also be addressed and whether giftedness is a stable trait which leads to gifted students performing similarly to experts or whether giftedness can be learned (Coleman and Shore 1991).

In conclusion, the current studies suggest that gifted junior high school students have comparable cognitive abilities to older students, but that they lack the knowledge base from which to draw on to solve nuclear physics problems. Results from this study provide two recommendations for teaching. Novices benefit from a well-defined method and introductory students benefit from exposure to a second method of solving a problem.

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Table 4. Competencies for generalized expert problem-solving skills.

- The ability to organize quantitative calculations through an understanding of qualitative relations
 - The ability to represent a problem situation via diagrams or drawings
 - The ability to organize one's knowledge according to principles that bear on the solution of the problem at hand
 - The ability to evaluate the validity of a provisional physical model through an analogy or chain of analogies
 - The ability to constantly search for other perspectives that may support or disconfirm previous ones
-

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