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ABSTRACT

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Cognitive Demands that Arithmetic Word Problems Impose on Children*

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Abstract

In order to determine how children cope with some of the demands imposed on them by arithmetic word problems, 200 sixth-graders were asked to solve problems modeled after those used by the National Assessment of Educational Progress. A quantitative demand was imposed on the children by adding extraneous information to the problems, whereas a verbal demand was imposed on them by increasing the syntactic complexity of the problems. Multiple regression analyses indicated that the children's computational ability and reading ability together accounted for 54% of the variance in solution accuracy: 8% and 14%, respectively, of this variance was unique, whereas 32% was common to the abilities. In addition, the analyses indicated that the presence of extraneous information in the problems reduced the accuracy of the children's solutions. The use of complex syntax, on the other hand, had no significant effect on accuracy. The findings suggest that reading ability and computational ability both play important roles in children's successful solution of word problems. The findings also suggest that the presence of extraneous information in word problems can impose a formidable demand on children's limited processing capacities.

Cognitive Demands that Arithmetic Word Problems Impose on Children

Systematic assessments conducted by the National Assessment of Educational Progress (1979) reveal that the arithmetic word problem scores of elementary school children have declined over the course of the past five years. One of the first steps that must be taken to improve children's performance is to identify the component abilities that contribute to successful solution of arithmetic word problems (Sherman, 1979, 1980).

Authorities agree that computational ability is essential for solving arithmetic word problems; however, they disagree over the relative importance of reading ability. For example, Aiken (1972) concluded that reading ability probably plays a major role in the solution of arithmetic word problems. Balow (1964) and Knifong and Holtan (1976, 1977), on the other hand, concluded that reading ability plays a minor role, particularly when the children are familiar with the vocabulary words used in the problems:

1. Computation is a much more important factor in problem solving than is reading ability (Balow, 1964, p. 21).
2. It is difficult to attribute major importance to reading as a source of failure (Knifong & Holtan, 1976, p. 111).
3. We sought evidence of poor reading abilities affecting children's success on word problems but found little such evidence ... The best recommendation for teachers is (1) help students develop computational skills, and (2) do not expect work on

reading skills (which may be valuable in its own right) to correct word problem difficulties (Knifong & Holtan, 1977, p. 229-230).

Balow's (1964) conclusion is questionable because he partialed out the total IQ of his sixth-graders before he assessed the influence of their reading ability. Since verbal abilities and quantitative abilities are two major components of total IQ, it makes little sense to control for them when assessing the effects of reading ability and arithmetic ability. Knifong and Holtan's (1976, 1977) conclusions are also questionable. They did not directly assess the reading ability of the 35 sixth-graders in their sample. Instead, they based their conclusions about reading ability on inferences they made about the kinds of errors their subjects made, and on the interviews they later conducted with their subjects.

When children attempt to solve arithmetic word problems, they must cope simultaneously with two kinds of demands: quantitative and verbal. Quantitative demands are associated with the identification and manipulation of the numerical information needed to solve the problems. Verbal demands, on the other hand, are associated with the text in which the numerical information is embedded. The presence of formidable quantitative and verbal demands could tax children's processing capacities and "block" their efforts to identify and manipulate essential information (Baddeley & Hitch, 1974; Kahneman, 1973; Kerr, 1973; Posner, 1982). For present purposes, processing capacity is defined as "the limited pool of energy, resources, or fuel, by which some cognitive operations or processes are mobilized and maintained" (Johnston & Heinz, 1978, p. 422).[1]

Children cope with the quantitative demands of arithmetic word problems by calling upon their computational ability; similarly, they cope with the verbal demands by calling upon their reading ability. One purpose of the present study is to determine the relative importance of each of these abilities to the solution of arithmetic word problems. It is hypothesized that computational ability and reading ability each account for significant amounts of variance in the accuracy of solutions. The arithmetic word problems used in the present study are modeled after those used by the National Assessment of Educational Progress.

In the "real world," individuals who solve mathematical problems for a particular task (e.g., architecture or navigation) must distinguish between relevant and extraneous information. For example, consider the owner of a tropical fish store who reads the following description of the aquarium he has just received: rectangular, stainless steel with unbreakable glass; weight is 5 pounds; height is 2 feet; length is 4 feet; width is 1 foot; capable of withstanding pressure of 40 pounds per square inch. In order to determine the volume of his aquarium, the owner must attend to some data and ignore the rest.

In contrast, in elementary school mathematics classes, teachers typically do not include extraneous information in the problems they present to children. Of course, when children are first learning to use a principle, the inclusion of extraneous information would probably not be advisable because interference would be generated. After the basic principle is understood, however, teachers might consider including extraneous information in the children's problems. Since the children must cope with extraneous information when they tackle applied problems later in life, they probably should learn to recognize it and to respond to it in classroom situations. Before recommendations can be made about curricula design, however, it is important to determine how the presence of extraneous information influences the problem solving performance of children. In the present study, a quantitative demand was imposed on children by adding extraneous information to problems. It was hypothesized that the presence of such information could tax the children's limited processing capacities and, thereby, reduce the accuracy of their problem solutions.

In real life, arithmetic problems are often embedded in textual formats. For instance, to solve problems in fields as diverse as archeology, geology, and economics, individuals must extract numerical data from documents such as letters, memos, and technical reports. Sometimes the syntax (i.e., the arrangement of words in sentences) of these documents is simple; however, all too often it is quite complex. In the present study, a verbal demand was imposed on children by increasing the syntactic complexity of problems. By taxing the children's processing capacities, the use of complex syntax could reduce the accuracy of their problem solutions.

Method

Subjects and Design

The subjects were 200 sixth-graders (109 girls and 91 boys) from two middle schools located in a university community. There were two individual difference variables, students' reading ability and their computational ability, and there were two format variables, problem information (absence vs. presence of extraneous information) and syntactic structure (simple vs. complex syntax). The measures of task performance were: the number of problems correctly answered, the number of problems correctly set up, and the amount of time spent taking the test.

Materials

The experimental materials included the Comprehensive Tests of Basic Skills (1976) and a 15-item arithmetic word problem test that was constructed specifically for this study.

Comprehensive Test of Basic Skills. The Comprehensive Test of Basic Skills was administered to all subjects. Scores on the reading comprehension subtest and the arithmetic computation subtest provided measures of the subjects' reading ability and computational ability, respectively.

The reading comprehension subtest consists of 45 multiple-choice questions designed to measure comprehension after reading short passages. The KR 20 reliability coefficient for this subtest is .96.

The arithmetic computation subtest is composed of 48 multiple-choice items designed to measure the ability to perform the operations of addition, subtraction, multiplication, and division. This subtest does not contain word problems. Its KR 20 reliability coefficient is .91.

Arithmetic word problems. A 15-item arithmetic word-problem test was constructed for use in the present study. The word problems were adaptations of sample problems supplied by the National Assessment of Educational Progress (1977). The problems tested the ability to add, subtract, multiply, and divide. Four versions of the test were formed by combining two versions of problem information (absence vs. presence of extraneous information) with two versions of syntactic structure (simple vs. complex syntax). The following problem illustrates the four versions:

No Extraneous Information - Simple Syntax

Joe had 131 pages left to read in his book. He then read 29 more pages. How many pages are left to read?

No Extraneous Information - Complex Syntax

If Joe had 131 pages left to read in his book and he then read 29 more pages, how many pages are left to read?

Extraneous Information - Simple Syntax

Joe had 131 pages left to read in his 529 page book. He then read 29 more pages. How many pages are left to read?

Extraneous Information - Complex Syntax

If Joe had 131 pages left to read in his 529 page book and he then read 29 more pages, how many pages are left to read?

In the versions with no extraneous information, all the numerical information given in a problem was necessary in order to obtain the correct answer. On the other hand, in the versions with extraneous information, one item of numerical information was not necessary. The problems in the versions with extraneous information were otherwise identical to those in the versions with no extraneous information.

In the versions with simple syntax, a problem consisted of three simple sentences. In the versions with complex syntax, these three simple sentences were combined, by means of the subordinating conjunction "IF" and the coordinating conjunction "AND," to form one complex sentence.

The average length of a sentence was 7.7 words in the simple syntax versions and 26.5 words in the complex syntax versions.

Procedure

In eight sixth-grade mathematics classes, the four test versions were randomly assigned to 200 students with the restriction that an equal number of students receive each version. The experimenter read the instructions aloud. The students were encouraged to work as carefully and as quickly as possible and were reminded to show all their work:

> Work as carefully and as quickly as possible. Your score depends upon you getting the correct answers as quickly as you can. I will be timing you. Also, you must show all of your work to receive credit for your answer. If you think you know how to solve a problem, but can not do the calculations, show how you would set it up. Besides wanting to see correct answers, I am interested in <u>how</u> you solve the problem. You may work on the problems in any order you wish. When you have finished all of the problems, turn over your paper and raise your hand. I will record your time and collect your test. Then, you may read your library book until everyone finishes.
>
> Any questions? Now, you can turn over your test booklet and begin.

During the test, the experimenter and the teacher circulated around the classroom to ensure that students did their own work. Neither the experimenter nor the teacher gave advice to any of the students. When a subject finished the task and raised his or her hand, the subject's test-taking time in seconds was recorded. Silent, electric digital timers were used for this purpose.

Performance Measures

Three measures of performance were used to assess the solution of arithmetic word problems: (1) total correct answers, (2) total correct set ups, and (3) total test-taking time.

Correct answers. Subjects received one point credit for each problem that had been carried out correctly and whose final answer was correct. Thus, subjects applied the correct operation (i.e., addition, subtraction, multiplication, or division) to the appropriate numbers, and computed the correct final answer.

Correct set ups. Subjects received one point credit for each problem that had been carried out correctly, even if the final answer was incorrect. If a subject applied the correct operation to the appropriate numbers, but made a computation error, he or she still received one point credit for the problem. Thus, correct set ups was a more liberal measure of problem-solving accuracy than correct answers.

Test-taking time. When a subject raised his or her hand, test-taking time was recorded in seconds. This measure indicates how much time the test was in the subject's hands. It does not indicate how much time was actually spent on task-relevant as opposed to task-incidental activities such as daydreaming.

Results

The influence of two individual difference variables, reading ability and computational ability, and two format variables, problem information (absence vs. presence of extraneous information) and syntactic structure (simple vs. complex syntax), on problem solving performance were assessed. There were three measures of performance: correct answers, correct set ups, and test-taking time.

First, means and standard deviations for the independent variables and the performance measures were computed. Second, significant correlations among the ability variables, the format variables, and the performance measures were identified. And third, the relative contribution of each ability variable and each format variable to performance was determined by means of hierarchical regression analyses.

Means and Standard Deviations

There were 109 girls and 91 boys whose reading abilities ranged from 1.4 to 11.9 (M = 6.29; SD = 2.77). Their computational abilities ranged from 1.0 to 11.9 (M = 6.31; SD = 1.91).

The students correctly answered 58% of the 15 problems (M = 8.68; SD = 4.22) and correctly set up 61% of the 15 problems (M = 9.11; SD = 4.34). Their test-taking times ranged from 303 seconds to 1860 seconds (M = 907.67; SD = 308.99).

Correlational Analyses

As can be seen in Table 1, reading ability and computational ability

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Insert Table 1 about here

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were positively correlated (p < .001). In addition, reading ability was positively correlated with correct answers and set ups (both ps < .001), and negatively correlated with test-taking time (p < .01). Similarly, computational ability was positively correlated with correct answers and set ups (both ps $< .001$), and negatively correlated with test-taking time ($p < .05$).

The presence of extraneous information was negatively correlated with correct answers ($p < .001$) and set ups ($p < .001$), and positively correlated with test-taking time ($p < .001$). Syntactic complexity was not significantly correlated with any of the performance measures.

Multiple Regression Analyses

In a predetermined order (Cohen, 1968, 1978; Nie, Hull, Jenkins, Steinbrenner, & Bent, 1975), two blocks of variables were entered into a regression equation that was applied to each of the following performance measures: correct answers, correct set ups, and test-taking time. Within each of these blocks, there were two variables.

Reading ability and computation ability were the variables included in the first block. Problem information and syntactic structure were included in the next block in order to determine if these variables added significantly to the variance already accounted for by the ability variables.

Within each block of variables, the variable that had the largest squared partial correlation with the performance measure was the one to enter first. In this way, the order and the relative contributions of the variables within each block were established.

Correct answers. This regression analysis is summarized in Table 2. In the first block of variables, reading ability entered into the equation

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Insert Table 2 about here

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first, accounting for 46% of the variance in total correct answers, F (1, 198) = 168.36, $p < .001$. The variance accounted for increased significantly to 54% when computational ability entered into the equation, F (1, 197) = 32.31, $p < .001$. A commonality analysis (Kerlinger & Pedhazur, 1973) indicated that reading ability and computational ability uniquely accounted for 13.6% and 7.6%, respectively, of the variance in total correct answers (see Table 3). The variance uniquely accounted for by a variable is defined here as the variance

Insert Table 3 about here

it accounts for when it is entered last within its block. The commonality analysis also indicated that 32.4% of the variance accounted for was common to both reading ability and computational ability.

In the second block of variables, problem information entered first and the total variance accounted for by the equation increased significantly to 67%, F (1, 196) = 79.93, $p < .001$. In other words, after the influences of the students' abilities are taken into account, the findings indicate that more problems were correctly answered when extraneous information was absent (M = 10.25) than when it was present (M = 7.11, see Table 4). Syntactic structure did not add significantly to the variance accounted for when it entered into the equation.

Insert Table 4 about here

Correct set ups. In the first block of variables, reading ability again entered the regression equation first (see Table 2), accounting for

45% of the variance in total correct set ups, $F(1, 198) = 160.97$, $p < .001$. When computational ability entered, the variance accounted for increased significantly to 51%, $F(1, 197) = 24.34$, $p < .001$. A commonality analysis showed that reading ability and computational ability uniquely accounted for 14.5% and 6.1%, respectively, of the variance in correct set ups; 30.3% of the variance accounted for was common to both ability variables.

In the second block of variables, problem information entered first, significantly increasing the total variance accounted for to 66%, $F(1, 196) = 90.08$, $p < .001$; thus, more problems were set up correctly when extraneous information was absent ($M = 10.84$) than when it was present ($M = 7.38$, see Table 4). Syntactic structure did not add significantly to the variance accounted for when it entered the equation.

Test-taking time. In the first block of variables, reading ability entered the equation first (see Table 2), accounting for 5% of the variance in test-taking time, $F(1, 198) = 9.98$, $p < .01$. The variance accounted for did not increase significantly when computational ability entered. A commonality analysis indicated that reading ability and computational ability uniquely accounted for 2.3% and 0.1%, respectively, of the variance in test-taking time; 2.5% of the variance accounted for was common to both ability variables.

When problem information entered the equation in the second block, the total variance accounted for increased significantly to 13%, $F(1, 196) = 18.11$, $p < .001$; test-taking times were faster when extraneous information was absent ($M = 819.88$ sec.) than when it was present ($M = 995.46$ sec., see Table 4). Syntactic structure did not significantly increase the variance accounted for when it entered the equation.

Discussion

The ability and format variables influenced the two measures of accuracy, correct answers and set ups, in similar ways. In order to avoid redundancy, only the influences on the correct answer measure will be discussed.

For the 200 sixth-grade students who participated in the present study, both reading ability and computational ability contributed to success in solving the arithmetic word problems. Together, reading ability and computational ability accounted for about 54% of the variance in correct answers. Reading ability uniquely accounted for about 14% of the variance in correct answers, whereas computational ability accounted for about 8%. In short, these findings support the hypothesis that reading ability plays a major role in the solution of arithmetic word problems. Apparently, the conclusions to the contrary that were drawn by Balow (1964) and Knifong and Holtan (1976, 1977) were premature and based on limited empirical evidence.

Thirty-two percent of the variance in correct answers that was accounted for by reading ability and computational ability was variance that was common to both variables. Thus, the variance common to both variables was relatively large -- larger, in fact, than the sum of their unique contributions. Since students integrate their reading and arithmetic skills when they solve arithmetic word problems, mathematics teachers should take both of these skills into consideration when evaluating students and providing them with feedback.. This advice is in opposition to that of Knifong and Holtan (1977):

> The best recommendation for teachers is (1) help students develop computational skills, and (2) do not expect work on reading skills (which may be valuable in its own right) to correct word problem difficulties. (p. 230)

Knifong and Holtan's advise is highly questionable in light of the present findings; when attempting to correct word problem difficulties, teachers should take into consideration students' reading skills.

In the method classes used for the training and continuing education of teachers, the integration of reading and writing skills is given great emphasis. In such classes, similar emphasis could be given to the integration of reading and computational skills. Such emphasis could help mathematics teachers to increase their awareness of basic reading processes, and reading teachers to increase their awareness of basic arithmetic processes. This increased awareness would have an impact on these teachers' lesson plans. For example, the lesson plans of reading teachers could include activities designed to enhance students' comprehension of passages that deal with problems in mathematics and science. Similarly, the lesson plans of mathematic teachers could include activities designed to (a) help students comprehend new vocabulary words (e.g., "fraction," "ratio," and "percentage"), and (b) help students reduce complicated word problems to a set of simple, relevant propositions (i.e., the basic idea units required to solve the problem).

Test-taking time is a crude criterion of performance when compared to the primary criteria, the accuracy measures -- it is not surprising, therefore, that reading ability and computational ability accounted for only about 5% of the variance in test-taking times. The variances, associated with both abilities in common (2.5%) and reading ability alone (2.3%), were higher than that associated with computational ability alone (0%).

In the present study, the presence of extraneous information in the word problems was an important factor, accounting for about 13% of the variance in correct answers and about 8% of the variance in test-taking times. Extraneous information reduced the accuracy of students' answers and increased the length of their test-taking times. These findings are consistent with the notion that extraneous information can impose formidable demands on students' limited processing capacities.

Apparently, the variation in sentence complexity was too superficial to impose differential demands on students' processing capacities. Problems in the format of three simple sentences and problems in the format of a complex sentence were solved with equivalent accuracy and speed. Assuming that other factors are held constant, these two syntactical variations can be used interchangeably by teachers when constructing their classroom tests.

In conclusion, since reading and computational skills both contribute significantly to success in solving arithmetic word problems, teachers (and text authors) are encouraged to design activities that will help students to integrate their basic skills and apply them effectively. In addition, teachers and text authors are encouraged to embed their word problems in realistic contexts that contain some extraneous bits of information.

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Table 1

Intercorrelations Among Independent and Dependent Variables

Variable	1	2	3	4	5	6	7
1. Reading Ability		.61***	-.00	-.03	.68***	.67***	-.22**
2. Computational Ability			-.02	-.01	.63***	.60***	-.16*
3. Problem Information				.00	-.37***	-.40***	.28***
4. Syntactic Structure					-.02	-.02	.01
5. Correct Answers						.99***	-.22**
6. Correct Set Ups							-.20*
7. Test-Taking Time							

*$p < .05$ **$p < .01$ ***$p < .001$

Note. Levels of significance are for two-tailed tests. N = 200

Table 2

Regression Analyses on Performance Measures

Variable	Multiple R	R^2	R^2 Change	F
Total Correct Answers				
Reading Ability	.6779	.4596	.4596	168.36***
Computational Ability	.7319	.5357	.0762	32.31***
Problem Information	.8187	.6702	.1345	79.93***
Syntactic Structure	.8187	.6703	.0001	0.03
Total Correct Set Ups				
Reading Ability	.6696	.4484	.4484	160.97***
Computational Ability	.7135	.5091	.0606	24.34***
Problem Information	.8146	.6636	.1546	90.08***
Syntactic Structure	.8147	.6637	.0001	0.04
Total Test-Taking Time				
Reading Ability	.2190	.0480	.0480	9.98**
Computational Ability	.2216	.0491	.0012	0.24
Problem Infomation	.3599	.1296	.0804	18.11***
Syntactic Structure	.3600	.1296	.0001	0.01

***$p < .001$ **$p < .01$ *$p < .05$

Table 3

Commonality Analyses for Performance Measures

Variable	Variance (%)	B Weight[a]
Total Correct Answers		
Unique to Reading Ability	13.6	.47
Unique to Computational Ability	07.6	.35
Common to Reading and Computation	32.4	
R^2	53.6	
Total Correct Set Ups		
Unique to Reading Ability	14.5	.48
Unique to Computational Ability	06.1	.31
Common to Reading and Computation	30.3	
R^2	50.9	
Total Test-taking Time		
Unique to Reading Ability	02.3	-.19
Unique to Computational Ability	00.1	-.04
Common to Reading and Computation	02.5	
R^2	04.9	

[a]This column reflects beta weight after both variables were entered.

Table 4

Means and Standard Deviations for Performance Measures

Syntactic Structure	Problem Information: Extraneous Info Absent M	SD	Extraneous Info Present M	SD
	Total Correct Answers			
Simple Sentences	10.34	3.48	7.18	4.45
Complex Sentences	10.16	3.80	7.04	3.97
M	10.25	3.63	7.11	4.20
	Total Correct Set Ups			
Simple Sentences	10.94	3.55	7.46	4.58
Complex Sentences	10.74	3.77	7.30	4.07
M	10.84	3.65	7.38	4.31
	Total Test Taking Time (Sec.)			
Simple Sentences	828.70	266.99	978.86	328.67
Complex Sentences	811.06	287.02	1012.06	306.39
M	819.88	275.92	995.46	316.56

Note: Each of the above means is based on 50 subjects.

Footnote

1. Because the definition of processing capacity (cf. Johnston & Heinz, 1978) lacks precision, it has been interpreted in several ways (e.g., as capacity, as attention, and as mental energy). Despite its lack of precision, the processing capacity concept is useful because it helps to explain how the performance of children on arithmetic word problems is influenced by quantitative and verbal components of those problems.