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ABSTRACT

While logical reasoning skills are related to success in science, the relationship between thought and formal logic is not clear. Propositional Logic Test (PLT), error patterns of students' interpretations of logical proposition, and developmental patterns of the error type are described. Examined is the relationship between logical reasoning ability and school science grade in tenth-grade Western Australian students (N=226). The PLT, Test of Logical Reasoning (TOLT) and Nonsense Syllogisms Test were used for measuring the logical reasoning ability. Correlations of grade in science with the PLT (.57) and the TOLT (.63) were high and the three reasoning tests together explained approximately 45 percent of the variance in science grade. An error analysis was undertaken for each subtest of the PLT, conjunction, disjunction, biconditional and implication across three ability groups. A discussion of the use of the PLT success rate differences is included. (YP)

REASONING ABOUT LOGICAL PROPOSITIONS AND SUCCESS IN SCIENCE

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Reasoning About Logical Propositions and Success in Science

INTRODUCTION

Considerable evidence has accrued within the past decade that logical reasoning skills are related to success in science. Piburn (1980) demonstrated that success on Piaget's Balance and Shadows tasks was significantly correlated with achievement on a nationally administered and scored high school certificate examination for New Zealand students. Formal reasoning ability was shown by Mitchell and Lawson (1988) to be an important determinant of the ability to solve genetics problems and to interpret text material in college biology. Chandran, Treagust and Tobin (1987) found that formal thought was more influential than prior knowledge in predicting chemistry achievement. Enyeart, Baker and VanHarlingen (1980) reported a correlation of physics achievement with both inductive and deductive reasoning.

The relationship between thought and formal logic is highly controversial. Two related studies (Lawson, et al., 1978; Lawson, 1983) have shown that formal thought and the ability to interpret logical connectives are factorially distinct. However, Piaget's theory is <u>not</u> about the development of symbolic reasoning. Instead, he was concerned with the degree to which "the algebra of logic can help us to specify psychological structures and put into calculus form those operations and structures central to our thought process" (Piaget, 1957, pg.

xvii). It remained an open question to Piaget whether there were correspondences between the structures of logic and those of thought, but it is clear that he believed that "the subject's 'naive' logic (as far as it can be codified) is as far removed from that of the logician as the child's 'naive' physics is from that of the physicist" (Beth & Piaget, 1966, pg. 155).

Cognitive psychology is moving away from molecular explanations of the reasoning process, as witnessed by the rise of interest in such topics as schema theory, information processing, or generative learning. These 'top-down' models describe learning as a process that "organizes the information selected from the experience in such a way that makes sense to us, that fits our logic [italics added], or real world experiences, or both" (Osborne & Witrock. 1983, pg. 493). A continuing investigation of the ability to interpret formal logic should help to clarify the manner in which information is stored and transformed at the 'level of representation', and shed further light on the origin of persistent misunderstandings about scientific phenomena that have recently been uncovered among science students.

The Propositional Logic Test

The Propositional Logic Test (PLT) is a sixteen item test that measures a subject's ability to interpret truth-functional operators by identifying instances that are consistent or inconsistent with a stated rule. The test was developed and trialled over a number of years by the science education faculty and students at Rutgers University.

The PLT contains four subtests of four items each. The subtests are defined by the logical operators that constitute the four 'well-formed' statements of propositional logic (Gale, 1979). These are the conjunction, disjunction, material equivalence and material implication. The formal notation for each of these operators involves the use of the connectives _and_, _or_, _if...and only if_, and _if...then_. In actual use in the PLT, the subtest of the disjunction is presented only as an inclusive disjunction, and the material equivalence is simplified to the more easily understood biconditional.

Initial design of the PLT was guided entirely by the formal rules of deductive logic. Subsequently it was submitted to a panel of four logicians for validation. All agreed that the PLT accurately reflected the logical meaning of the four operators.

Each item of the PLT consists of a propositional statement, in binary form, followed by the four instances that represent all

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insert Figure 1 about here

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combinations of the presence or absence of attributes mentioned in the stem. The subject is then asked to circle all instances that are allowed by the sentence, and to cross out those that are not (Figure 1).

A complete and unequivocal error analysis of responses to the PLT is possible because the instrument is constructed of two-valued logical propositions, with each followed by the four instances of a binary truth table (p.q, p.q, p.q, p.q). Since each of the four instances is to be marked by either a cross or a circle, there are sixteen, and sixteen only, possible complete answers to each item. These correspond to the truth tables of the sixteen binary operations used by Piaget in his analysis of logical thought. With no intention to be, or implication of, testing Piaget's theory concerning the correspondences of thought and logic, the nomenclature of this system has been adopted for the analysis of error patterns.

Misconceptions About Logical Propositions

Under normal conditions of error, one would expect answers to individual items on the PLT to be randomly distributed through all truth tables. This is not the case. Pallrand, et al. (1981), in a sample of nearly 2,000 college students, found that only nine of the sixteen possible truth tables were used more than 1% of the time. A smaller sample was selected for clinical interview. The results demonstrated that error was systematic and consistent, and reflected an underlying structure to students' interpretations of logical propositions.

A major error pattern was the use of the truth table of the conjunction across all items. This occurred approximately 20% of the time in the case of biconditional and implication statements. In many of the clinical interviews, subjects who were given the correct interpretation of conditional statements modified their answers and demonstrated their ability to use the correct truth table. However, more than half of those interiewed refused to agree with this new interpretation. In a clinical interview where a student was being asked to make judgments about the statement "if it is small then it is square", s/he would admit only the small squares into an 'allowed' category. When questioned about this, s/he said:

S. I just interpret it if it is small it is square, and that's what you put in the allowed.
I. You mean you just put small...what do you put in allowed?
S. Small <u>and</u> square.
I. Say it again, I'm sorry.
S. The small <u>and</u> the square.
I. Small <u>and</u> square?
S. If it's small it's square, and that's what you put in there.

Another refused to agree with a correct interpretation of the implication, and complained that the <u>If...then</u> construction was confusing. When asked how to correct the wording, s/he replied, "Say <u>and</u>.'

Another group was successful at both the conjunction and disjunction but continued to use the conjunction on biconditional and implication items. There was some tendency among this group to overgeneralize the use of the truth table of the disjunction, and to use it inappropriately on a variety of other items.

A third major error appeared when students chose either the antecedent (p) or the consequent (q) condition of the stem as correct, and marked the remaining choices incorrect. This appeared to result from a specific misunderstanding of the meaning of a conditional statement. The following transcript records a clinical interview with a student who had been asked to test the proposition that "all turtles with diamonds on their back have green bellies." The student is considering cardboard replicas of possible turtles during an instance evaluation:

S. They've got diamonds, so they've got green bottoms.
E. But...are you sure they've got green bottoms?
S. Yeay, because they've got diamonds.
E. But how about if you flipped them over and found out they had red bottoms?
S. Flip them back over.
E. (chuckle)...They don't count, huh?
S. I still say I wouldn't flip over the diamond ones...
E. All right.
S. If they've got diamonds then they're green. I'd flip over the red bottomed ones to see if they've got diamonds, then they're green.
E. (long pause)...Run that by me one more time.
S. I'd flip over the red ones, because, if they had diamonds then I could count them as green.
E. How could you count them as green? They would have...
S. Because, if they've got diamonds then they're green.
E. But they're red!!!!
S. But...if they've got diamonds, then they're green.
E. (laugh)...So you're telling me that the hypothesis has to be true, no matter what.

In terms of the analysis of the PLT, this interpretation appears as the truth table of the logical operation "affirmation of p". When presented with a correct interpretation, subjects appeared able to use it, but disagreed that it was an appropriate way to think about the statement.

Another error, used most commonly by subjects who could complete the conjunction, disjunction and biconditional, was to use the truth table of the biconditional on implication statements as well. This error, which is called the "fallacy of affirming the consequent" is quite a common one, and always warned against in beginning logic texts. A related, but infrequent error was to reverse the statement (recriprocal implication), but without assuming that it reads both ways.

Two minor remaining error patterns were the use of tautology, in which all choices are seen as correct, and the exclusive disjunction rather than the inclusive disjunction.

Developmental Trends in Misconceptions

A developmental pattern of error type was revealed in a study of 275 students from grades seven through twelve (Piburn & Enyeart, 1981). In this study, the data consisted of the truth table used in each of the sixteen items, without concern for its actual content. Under this condition, answers should be distributed equally among each of the four correct truth tables.

The earliest error pattern was to treat the sixteen propositions as though they were all conjunctions. In the seventh and eighth grades, between 50% and 60% of the items were answered with the truth table of the conjunction, and fewer than 6% with the truth tables of either the biconditional or implication. This can be compared with expected frequencies of 25% for each truth table if the items were all answered correctly.

Between the eighth and ninth grade, the use of the truth table of the disjunction had risen to 25-30%, and use of the conjunction had dropped to the same level. However, use of the biconditional or implication truth tables remained at a level of 6-8% each. This appeared to represent a transition, from an incorrect interpretation of disjunction as conjunction, to a correct analysis. There was no corresponding change in interpretation of the biconditional or implication.

In fact, there was no increase in the use of such truth tables until the eleventh grade, when the frequency of biconditional truth tables rose to 17% and of the implication truth tables to 11%. By the college level, the rate of error on the biconditional and implication items had not changed appreciably (Pallrand, et al., 1981).

METHOD

The sample for this study consists of all tenth year students in two parochial single-sex schools in Western Australia, and contains 98 males and 128 females. The decision to use these two schools arose from the desire to obtain well matched samples of males and females who had equivalent background and experiences in science.

These schools are only one mile apart, and enroll similar students, often from the same family. Students are from a middle class background, and are often first generation immigrants. Fathers are typically white collar or trade workers, and mothers work. Despite this middle to lower SES profile, students score better than average for other Western Australian schools, and a smaller number leave school after year ten and enter the trades. Between 80 and 90 percent continue in school to year eleven, which is designed for the college bound student.

All students in Western Australia complete a comparability examination at the end of year nine that covers the core areas of English, Mathematics, Social Studies and Science. The results of this examination are used to place students in one of three tracks. The goal is to divide all students in the state so that 25% are advanced, 50% intermediate, and 25% basic. In the schools used in this study, results of the comparability exam allowed administrators to place approximately 35% of the students in advanced and 15% in basic tracks.

These results are further used to adjust test scores across schools, so that a particular grade received at one school would be completely comparable to the same grade received at any other school in the state. This is monitored by a Moderator from the Department of Education who visits each school once every two years and reviews student files. As a result, it was possible to use science grades in both schools as dependent variables in this study, with complete assurance from officials of the schools and the West Australian Education Department that they were fully equivalent.

All students were enrolled in the same General Science Curriculum. This consisted of seven modules, of which five were required of all students, and the remainder only of students in the Advanced track. The topics were nuclear energy, ecology, sight and sound, light, genetics, motion and chemistry. Final grades were assigned on the basis of school-made tests consisting of multiple choice and short answer items that were given twice during the year (80%), as well as laboratory reports and homework (20%).

Three conceptually different measures of logical reasoning ability were administered to these students. The first was the Propositional Logic Test (PLT). The other two were the Test of Logical Reasoning (TOLT) and the Nonsense Syllogisms Test.

The TOLT is a ten item group test of logical thinking (Tobin & Capie, 1981). Each item requires a response and a justification, and both must be correct to receive credit for the item. The instrument is based upon Piaget's theory, and measures five modes of formal reasoning: controlling variables, proportional reasoning, combinatorial reasoning, probabilistic reasoning and correlational reasoning. Coefficient alpha for the TOLT, based upon a sample of 682 students, was reported by

Tobin and Capie (1981) to be .85.

The Nonsense Syllogisms Test was taken from a factor-referenced battery of cognitive tests (Ekstrom, et al., 1976). It is one of four instruments contained within the Logical Reasoning aptitude factor from that battery. The authors report a reliability of .64 on this instrument for a sample of 189 high school males.

All statistical analyses for this study were conducted on an Apple IIe microcomputer (Bolding, 1985).

RESULTS

The KR-20 reliability of the PLT for the sample of 226 students was .82 (Table 1). This is slightly lower than earlier

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reliability estimates of .90 (Enyeart, et al., 1980) for a sample of 30 college students or of .94 (Pallrand, personal communication) for a sample of 34 high school students.

Mean scores on subtests of the PLT range from 2.9 on the conjunction to 0.6 on the implication. The average for the entire instrument of 6.3 from a possible 16 points is slightly lower than a previously unpublished average score of 7.7 obtained by the authors for a sample of 229 American ninth grade parochial school students. The highest reported average score on this measure is 10.7 for a sample of 1,990 American college freshmen (Pallrand, et al.. 1980).

Subtest reliabilities decrease in the order biconditional, implication, conjunction and disjunction. Lower reliabilities of the conjunction and disjunction may be reflecting their lesser difficulty, and be the artifact of a ceiling effect.

Item difficulties and discrimination indices are given in Table 2. The conjunction items are the least difficult, and the

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conditional items, consisting of biconditional and implication, the most difficult. Despite the fact that they are almost eqial in difficulty, the biconditional items have higher discrimination indices than the implication items.

The highest correlations are between the biconditional and implication subtests of the PLT (Table 3). This is not

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surprising, since the two both consist of "conditional" items, and are conceptually interrelated. Correlations of these with the disjunction subtest are lower but still significant. The conjunction does not correlate significantly with the other subtests.

A correlation matrix (Table 4) for the variables used in

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this study reveals that the strongest relationship among measures of reasoning ability is between the PLT and the TOLT. The correlation between these two very different measures is .63. The nonsense Syllogisms Test is significantly correlated with both, but the correlations are only .17 with the PLT and .16 with the TOLT. This may result in part from the fact that the Nonsense Syllogisms Test was very difficult for all subjects, and scores were low. Correlations of grade in science with the PLT (.57) and the TOLT (.63) were high, and of almost the same magnitude. The Nonsense Syllogisms Test did not correlate significantly with science grade.

The relationship of ability and success on the PLT is shown in a somewhat different format in Table 5. The means and

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standard deviations of advanced, intermediate and basic students are shown for males and females. In both instances, the advanced students receive the highest scores and basic students the lowest, and in both cases the greatest difference is between advanced and intermediate students. There is no apparent difference between the scores of males and females in intermediate and basic groups, but advanced females score appreciably higher than their male counterparts.

Since the PLT and TOLT are highly correlated, and correlate in addition at about the same magnitude with science grades, a stepwise multiple regression analysis was conducted in order to assess the degree of independent contribution that each of the measures of reasoning ability might make to achievement in science (Table 6). The three reasoning variables together

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produce a multiple R of .67, and explain approximately 45% of the variance in science grade. The Beta weight of the TOLT (.45) is approximately 50% larger than that of the PLT (.29). But the PLT contributes to approximately 10% of the explained variance in science grade even after the variance shared by other measures has been removed.

An error analysis was undertaken for each subtest across the three ability groups. All three groups were relatively successful on the the conjunction (Table 7).

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Advanced students answered 83% of the questions correctly, while intermediate and basic students were only successful on 70-75%. In these two groups, the lower success rate on the conjunction was almost perfectly balanced by an increased use of the truth table of the inclusive disjunction. This is fairly typical of groups of students who are just learning to be successful at the disjunction, and typically overgeneralize this solution to other subtests.

There are dramatic differences between the success rate of advanced students and others on the disjunction (Table 8).

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Advanced students are correct on approximately three out of four (71%) of the items, whereas intermediate and basic students are successful only on one-third (33-40%). They are choosing the truth table of the conjunction on these items about 20% of the time. However, this alone does not explain the difference in success rate. Although all students make the error of choosing the affirmation of p as a response, this occurs twice as often for intermediate and basic students as for advanced.

Responses to the biconditional and implication subtests (Tables 9 & 10) tell a very similar story. Advanced students

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are successful on one-third of these items while other students are correct less than 10% of the time. Both groups tend to use the conjunction response instead, although this is twice as frequent for intermediate and basic students as for advanced. Both groups use the inclusive disjunction truth table, and with about equal frequency, in the case of the biconditional, and the affirmation of p truth table in the case of the implication.

DISCUSSION

The Propositional Logic Test is an easily administered and very reliable measure of the ability to interpret logical propositions. Despite the fact that they each consist only of four items, the subtests also yield high reliability coefficients.

The real strength of the PLT, in contrast to other measures of this ability, lies in the possibility of a complete and unequivocal error analysis. The response to each item can be interpreted as the truth table of one of the sixteen binary operations. If all truth tables were used with equal frequency, such an analysis would have little meaning, but this is not the case. Error patterns on the PLT show systematic patterns with page and with ability in science that almost certainly reveal underlying reasoning processes.

In his work on the logic of classes, Piaget demonstrated that the ability to flexibly sort objects into a multiplicity of subsets arises in children an at about the age of seven, and signals the onset of the stage of concrete operations. This logical operation is called the conjunction in the terminology of propositional logic, or the intersection in set theory. The truth table is represented in Figure 2. All subjects above the

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age of thirteen who have been tested with the PLT are successful on at least three out of four of the items in the conjunction subtest. In this study, students in all three ability levels in science achieved the same success rate. We have every reason to believe that this operation is firmly consolidated by adolescence, and probably long before.

The more interesting observation from this and other studies is that many people use this truth table inappropriately when presented with other propositional statements. This does not seem to be the result of simple misunderstanding. Rather, we would interpret this as the result of a structural limitation in the reasoning process that does not allow the use of other operations. Basic and intermediate science students commit this error 20% of the time on disjunction items and 40-50% of the time on conditional items.

Continuing his work with the logic of classes, Piaget demonstrated that a proper understanding of class inclusion did not develop until approximately the age of 9. This operation, in which a superordinate class is seen as the sum of two or more subordinate classes, is termed the disjunction in propositional logic or the union in set theory. It is diagrammed in Figure 3. Previous studies have shown that there

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is a sharp increase in the ability to correctly interpret the disjunction on the PLT around the age of 14. This is considerably older than suggested by Piaget's results with class inclusion tasks. Advanced students in this sample interpreted this operation correctly in 70% of the cases. Intermediate and Basic students were much less successful, and correctly answered these items only 30-40% of the time. Again, the latter groups tended to use the truth table of the conjunction on these items, while Advanced students did not.

Success with the implication operator requires the insight that only the p.q instances are not allowed by the statement, and that all others are perfectly acceptable. This relationship is diagrammed in Figure 4. A similar insight is necessary for

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completion of the biconditional. Working with a version of an implication contained within a 4-card hypothesis testing task, Wason and Johnson-Laird (1972) posited the existence of a falsification insight on the part of subjects who were able to realize that conditional statements are subject only to falsfication and cannot be proven true (Hempel, 1945). On interview, it is typical of subjects who are successful with the implication that they clearly identify the discovery of the single instance that will negate the implication as their goal. This point of view appears to develop with adolescence, and previous work suggests that students do not become successful with the implication or biconditional on the PLT until the eleventh or twelfth grade.

In this study, the Advanced group was successful on 30-40% of the conditional items, while the Intermediate and Basic groups answered no more than 10% correctly. Both groups made similar errors. The first was to use the truth table of the conjunction. The second, the affirmation of p, appears to result from a misunderstanding regarding the meaning of conditional statements, and their interpretation as definitions. These students do not see an implication as a hypothesis. Instead, they take it to be a statement such as "all bachelors are unmarried men". In this statement, any bachelor is <u>by definition</u> unmarried, and the statement is not hypothetical. On interview, such subjects appear fully able to understand either interpretation of the implication, but do not agree that their own is incorrect.

Success on the PLT correlates highly (r=.57) with success in science for these students. A corrollary is that students in different ability groups achieve very different scores on the instrument. In both instances, because of the unusual pattern of success on the PLT, those students who are more successful in science are also those for whom an ability to use conditional reasoning is evident. Students who are less successful are more likely to interpret all conditionals as conjunctions.

The question of the relationship between the ability to use propositional statements, formal thought, and success in science is complex. The PLT and TOLT are intercorrelated, and thus share some common elements. It is not surprising that the TOLT shares more variance with achievement in science than the PLT, since the items on the TOLT <u>are</u> science. Prior knowledge and experience of a good science student will certainly lead to a higher score on the TOLT. On the other hand, the Beta weight for the PLT after the variance shared with the TOLT is removed is still quite respectable. Most researchers, including Piaget, have recognized the importance of linguistic elements in success at tasks such as the PLT. It is possible, of course, that the additional variance which this measure explains in achievement in science results largely from a relationship with verbal ability. The results of interviews with subjects hint that language is not the main difficulty.

It is more likely that students for whom the mental structures of conditional reasoning are not present will not be able to learn much of what is contained within the science curriculum, or what they do learn is very different than what we might expect. If logical reasoning is a filter between experience and mental schemata, then the poorer performance in science of students who are not able to use the operations of conditional reasoning is perfectly easy to understand.

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EXAMPLES OF THE PLT BY LOGICAL OPERATOR

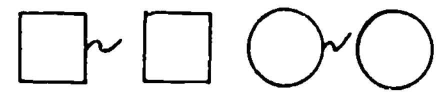
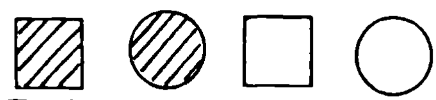
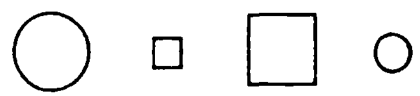
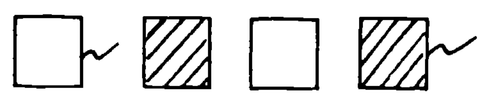
CONNECTIVE AND SYMBOLIZATION	NATURAL LANGUAGE STATEMENT	Figures, Symbolic Notation, and Truth-Values
Conjunction $p \cdot q$	It is square and it is tailed.	 $p \cdot q$ $p \cdot \bar{q}$ $\bar{p} \cdot q$ $\bar{p} \cdot \bar{q}$
Material Implication $p \supset q$	If it is white, then it is round.	 $\bar{p} \cdot \bar{q}$ $\bar{p} \cdot q$ $p \cdot \bar{q}$ $p \cdot q$
Biconditional $p \equiv q$	If it is round it is small and if it is small it is round.	 $p \cdot \bar{q}$ $\bar{p} \cdot q$ $\bar{p} \cdot \bar{q}$ $p \cdot q$
Disjunction $(p.q)v(pvq)$	It is striped or it is tailed or both	 $\bar{p} \cdot q$ $p \cdot \bar{q}$ $\bar{p} \cdot \bar{q}$ $p \cdot q$

Figure 1: Examples of Items from the four subtests of the PLT

Figure 2. A graphical representation of the truth table of the conjuction. Binary instances shown in the shaded area falsify the operation.

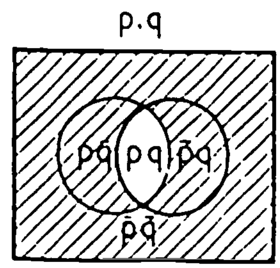


Figure 3. A graphical representation of the truth table of the disjunction. Binary instances shown in the shaded area falsify the operation.

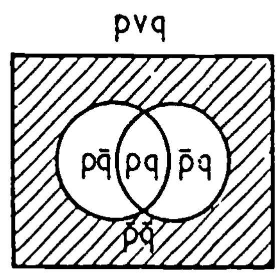


Figure 4. A graphical representation of the truth table of the implication. Binary instances shown in the shaded area falsify the operation.

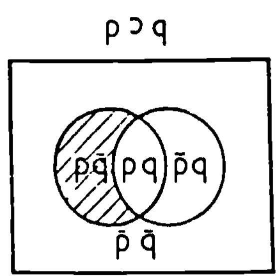


Table 1. Descriptive data for the PLT

	Possible Score	Mean	Standard Deviation	KR-20 Reliability
Subtest:				
Conjunction	4	2.93	1.39	0.790
Disjunction	4	1.98	1.44	0.733
Biconditional	4	0.73	1.37	0.907
Implication	4	0.62	1.23	0.870
TOTAL	16	6.26	3.53	0.824

Table 2. Item analysis for the PLT

Subtest	Item	Proportion Correct	Discrimination Index
Conjunction	1	0.75	0.29
	6	0.71	0.32
	9	0.76	0.27
	14	0.73	0.26
Disjunction	2	0.51	0.54
	5	0.61	0.49
	10	0.27	0.50
	13	0.59	0.52
Biconditional	4	0.18	0.71
	7	0.19	0.73
	12	0.20	0.71
	15	0.16	0.71
Implication	3	0.17	0.63
	8	0.16	0.69
	11	0.18	0.64
	16	0.11	0.59

Table 3. Intercorrelations of PLT subtests

	Conjunction	Disjunction	Biconditional	Implication
Conjunction	-	ns	ns	ns
Disjunction	ns	-	0.42	0.42
Biconditional	ns	0.42	-	0.63
Implication	ns	0.42	0.63	-

Table 4. Correlations of PLT with other measures of reasoning ability and with grade in science

	PLT	TOLT	Syllogisms	Grade
PLT	-	0.63	0.17	0.57
TOLT	0.63	-	0.16	0.63
Syllogisms	0.17	0.16	-	ns
Grade	0.57	0.63	ns	-

Table 5. Means and standard deviations on the PLT of males and females in advanced, intermediate and basic science courses

	MALE		FEMALE	
	n	mean (S.D.)	n	mean (S.D.)
Advanced	48	8.58 (4.21)	27	9.70 (3.64)
Intermediate	64	5.11 (2.34)	50	5.12 (2.19)
Basic	14	4.21 (1.31)	21	4.52 (2.20)

Table 6. Stepwise multiple regression analysis of grade in science on scores on PLT, TOLT and Syllogisms

Dependent Variable: Grade		
R = 0.667 R-square =0.445		
Independent Variable	Coefficient	B-weight
PLT	0.170	0.288
TOLT	0.311	0.451
Syllogisms	-0.015	-0.030
Constant	2.973	

Table 7. Response of students from three ability groups to the conjunction subtest of the PLT, showing the frequency with which the most commonly used binary operations are chosen (figures given as percentages).

	Advanced	Intermediate	Basic
conjunction	82.7*	69.9*	75.7*
affirmation of p	2.0	3.8	3.5
affirmation of q	2.0	5.1	4.9
inclusive disjunction	2.7	10.8	11.1
biconditional	4.0	3.5	0.0
implication	4.0	2.4	1.4
recriprocal implication	0.3	1.5	0.7

* correct answer

Table 8. Response of students from three ability groups to the disjunction subtest of the PLT, showing the frequency with which the most commonly used binary operations are chosen (figures given as percentages).

	Advanced	Intermediate	Basic
conjunction	5.0	17.5	20.8
affirmation of p	10.7	20.8	25.7
affirmation of q	9.7	14.6	9.7
inclusive disjunction	71.0*	40.0*	33.3*
biconditional	1.0	1.1	0.7
implication	0.0	0.9	0.0
reciprocal implication	1.0	1.1	3.5

* correct answer

Table 9. Response of students from three ability groups to the biconditional subtest of the PLT, showing the frequency with which the most commonly used binary operations are chosen as answers (figures given as percentages).

	Advanced	Intermediate	Basic
conjunction	20.0	40.5	45.8
affirmation of p	4.3	10.6	9.7
affirmation of q	6.7	16.4	22.9
inclusive disjunction	17.3	16.2	11.8
biconditional	39.7*	8.4*	4.2*
implication	6.3	3.3	1.4
recriprocal implication	4.0	2.9	2.1

* correct answer

Table 10. Response of students from three ability groups to the implication subtest of the PLT, showing the frequency with which the most commonly used binary operations are chosen as answers (figures given as percentages).

	Advanced	Intermediate	Basic
conjunction	20.3	39.8	45.8
affirmation of p	23.7	32.7	25.7
affirmation of q	4.0	3.5	8.3
inclusive disjunction	2.3	5.3	6.3
biconditional	14.7	5.3	4.9
implication	33.3*	8.8*	2.8*
reciprocal implication	0.3	1.1	0.7

* correct answer