DOCUMENT RESUME

ED 202 703 SE 034 996

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TITLE Cognitive Structure and Performance After Physics Instruction.
PUB DATE Apr 81
NOTE 29p.: Paper presented at the Annual Meeting of the American Educational Research Association (Los Angeles, CA, April 13-17, 1981).

EDRS PRICE MF01/PC02 Plus Postage.
DESCRIPTORS *Cognitive Processes; Grade 11; High Schools; High School Students; *Learning; *Performance; Performance Factors; *Physics; Science Education; *Science Instruction; Secondary School Science
IDENTIFIERS *Cognitive Structures; *Science Education Research

ABSTRACT

Two instructional programs with differing emphases on linking to existing knowledge and experience were used to present elementary dynamics to physics (N=67). Effects on aspects of cognitive structure and performance were investigated. Propositions elicited by a modified word-association technique were used to assess linking in cognitive structure between dynamics and existing knowledge. Performance differences were found between instructional groups for problems requiring the application of material learned to new situations. Path analyses indicated that this effect of instruction on performance was substantially mediated by the extent to which cognitive structure was linked to existing cognitive structure. (Author/JN)

COGNITIVE STRUCTURE AND PERFORMANCE

AFTER PHYSICS INSTRUCTION

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Paper presented at the meeting of the American Educational Research Association, Los Angeles, April 1981.

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The Context of the Study

This paper describes a study which sought to explore effects of differing instructional forms on aspects of cognitive structure and, in turn, the effects of these aspects of cognitive structure on performance.

The conceptual origins of this research are to a considerable extent derived from the work of Mayer, Greeno, et al., in particular from the inferences drawn about cognitive structure in that work (see Mayer, 1975 for a review). The first of these studies (Mayer & Greeno, 1972) was motivated by the idea that different instructional procedures could result in learning outcomes that were qualitatively or structurally different. In that study two instructional procedures were used. These focused, in one case, on a formula and the mechanical operations involved in using it (termed the Formula program), and, in the other, on relating the variables in the formula to the existing knowledge of the experimental subjects (termed the General Concept program). Two forms of performance tests were used to assess the nature of the learning resulting from this instruction. These were termed near transfer -- questions very similar to those given in instruction (e.g. substituting values into the formula), and far transfer -- questions which required interpretation (e.g. unfamiliar or unanswerable problems). It was found that subjects who had experienced instruction with emphasis on use of the formula exhibited better performance on near transfer problems whilst subjects who had experienced instruction with emphasis on relating to existing knowledge exhibited better performance on far transfer problems.

In order to explain this interaction between Instruction and Performance, the notions of internal and external connectedness in cognitive structure were invoked. Internal connectedness refers to the extent to which the concepts presented in instruction are related to one another in cognitive structure, whilst external connectedness refers to the extent to which these newly learned concepts are related to pre-instruction knowledge in cognitive structure. Given these postulated characteristics of cognitive structure, Mayer and Greeno argued that the two instructional forms used placed emphasis on generating either internal connections (the Formula program) or external connections (the General Concept program) in cognitive structure, and the two forms of assessment of learning required either internal connections (the near transfer scale) or external connections (the far transfer scale): hence the observed performance differences. Subsequent work has both replicated these findings and extended the ideas.

Two important questions arise from these studies. The first, important from the perspective of research, is whether or not the performance differences established in the studies are in fact the result of the suggested differences in cognitive structure. That is, whether or not the effect can be shown more directly and with less inference to be of the causal form: Instruction → Cognitive Structure → Performance. Consideration of this question requires some methodology for assessing those aspects of cognitive structure which have been argued by Mayer and Greeno to be significant.

The second question, important from the perspective of instruction, is whether or not the Instruction x Performance interaction found by Mayer and Greeno can be found in a normal instructional context (i.e. real classrooms, extended time for the learning of a complex topic, learning tasks from a number of subject areas being undertaken relatively simultaneously, etc.). The large bulk of instruction has as one of its prime purposes the development amongst students of the ability to apply the material presented to situations other than those covered by the instruction -- in other words, the development of forms of far transfer performance. If instructional differences of the form used by Mayer and Greeno can be shown to have impact on performance in a more normal learning situation, there would be clear and substantial implications for instruction.

In experimentally considering the first question (can the cognitive structure features hypothesized by Mayer and Greeno be more directly shown to account for the observed performance differences?), it is clear that an empirical consideration of the general paradigm Instruction → Cognitive Structure → Performance is also being undertaken. Although Thro (1978) has shown that an aspect of memory (associative structure) which developed through instruction contributed significantly to achievement after instruction, the present research provides a stronger test of the validity of this view of learning for the following reasons. In this case it is argued à priori that different instructional forms will produce particular cognitive structure differences, and it is known that, under laboratory conditions for particular subject matter, these instructional forms will produce performance differences. Hence the hypothesized causal links in the three-stage paradigm are more tightly specified than in the case of the investigation by Thro and, it would seem, are more clearly rooted in an underlying theory.

Given this context for the research, a methodology for probing internal and external connectedness in cognitive structure was required.

A Methodology for Describing Relevant Aspects of Cognitive Structure

One of the strong influences on the choice of the methodology used was a concern with the impact of a cognitive structure probe on cognitive structure itself. The potential for interaction between probe and cognitive structure is perhaps best illustrated by considering one of the three modes suggested by Rumelhart and Norman (1978) to be involved in the learning of complex topics. These modes are accretion, restructuring, and tuning. The notion of restructuring -- the reorganization of knowledge/cognitive structures involving the topic -- describes well the impact on cognitive structure of some probes. This effect is particularly obvious in the case of strategies which call on respondents to reconsider statements and observations (see, for example, Champagne, Klopfer & Anderson, 1980; Gunstone & White, in press). Although the interaction between probe and cognitive structure can frequently be argued to not be of importance, in the present case the impact of instruction on cognitive structure was a fundamental consideration. Consequently it was important to minimize other effects on cognitive structure, in particular effects of the instrument for assessing the aspect of cognitive structure under consideration.

Of the techniques for probing cognitive structure which have previously been used, one appears to in fact minimize this interaction. That technique is word association (WA) used in a topic specific sense by, amonst others, Shavelson (1972). In those studies respondents were given a stimulus word such as force and asked to think like a physics student whilst giving associative responses. The specific advantages of this approach in terms of minimizing the probe/cognitive structure interaction are the lack of prompts other than the stimulus word and the lack of emphasis on introspection and reconceptualization. However the approach also has clear problems.

Recently a number of writers have advanced criticism of a most cogent nature about this use of WA (e.g. Pines, 1977, pp. 88-100; Strike & Posner, 1976). These criticisms can essentially be summarized in one sentence. Although the WA technique can be argued to indicate some perceived propositional relationship between two concepts (e.g. Miller, 1969), it neither indicates what that relationship is, nor gives any data to allow inferences to be drawn about the relationship. In the present study, the requirement to categorize relations between concepts as either external or internal connections throws this WA criticism sharply into focus.

The solution to this problem seems simple -- ask respondents for the propositional connection they perceive between a WA stimulus and a WA response. In this study, respondents were asked to give associations to a particular stimulus and then to go back and write, for each response, a sentence which contained the stimulus and the response. They were also instructed to write each sentence so that "it shows the way you see your word (i.e. the response) connected with" the stimulus. Such an approach allows for the retention of the previously argued advantages of WA whilst also giving substantive data about the perceived relationship between stimulus and response.

This form of probe of aspects of cognitive structure is termed a word association/generated proposition test (WA/GP). As used in this study, the WA/GP test instructed students to think like physics students whilst responding, and gave students one minute to respond with associations to a stimulus. The development of this test format, together with the data leading to the decisions to impose these restraints and to accept the generated proposition as a valid indicator of the propositional link between concepts has been described elsewhere (Gunstone, in press).

Having obtained this information about the propositional links between a particular concept (the stimulus) and other concepts seen by the respondent to be related to the stimulus (the responses), some method was required for determining which propositions represented internal connections and which represented external connections. To some extent this is a function of the totality of the individual's cognitive structure. For example, a proposition relating concept A to stimulus X would be an internal connection for a respondent who has no cognitive structure relevant to A except that proposition. The same proposition would be an external connection for a respondent who had, before instruction involving concept X, an existing cognitive structure relating to A which was now connected to X cognitive structure by the proposition. However it would require a detailed description of the totality of an individual's cognitive structure before this sort of idiosyncratic judgment of internal/external connectedness could be attempted. Hence it was necessary to operationally define internal/external connectedness in a manner consistent with the way these terms were used in other aspects of this study.

Internal connections were defined as propositions which were relationships or definitions. Other physics related propositions were judged to represent external connectedness, whilst the very small number of propositions which were obviously unrelated to physics were left as a residual. This rule-for-decision was suggested in particular by the description given of internal connections in the Mayer, Greeno, et al. studies.

The Design and Conduct of the Study

The two broad questions underlying the study have been given above (pp. 3-4). One of these concerned the robustness in the mileau of a normal instructional setting of the Instruction x Performance interaction found by Mayer, Greeno et al. As a consequence, the study was undertaken in school classrooms.

Intact 11th grade physics classes received instruction in Newton's Laws as part of their normal course, and in the normal sequence of that course. Two schools were randomly selected from a pool comprising schools with two grade 11 physics classes taught by the same teacher. Further, schools were included in the pool only if no forms of selection (either overt or covert) could be identified in the methods used to form the two physics classes. In each of the schools selected, the classes were randomly allocated to the two instructional methods which were used. Data from 67 students were obtained.

Although it is clear that the above procedure has not resulted in a random allocation of students to treatments, it is argued that this end has been pursued as far as possible within the limitations imposed by the use of intact classes in the education system in which the study was conducted.

The use of a naturalistic setting then resulted in constraints on the experiment. Conversely, the conduct of an experiment placed constraints on the extent to which the setting could be naturalistic. In particular, printed learning materials, rather than teachers were used for the two instructional forms because of a need to ensure that the instruction given in each group followed the desired focus.

The initial intent for the instructional programs was that they should parallel the forms used by Mayer and Greeno (1972). However the logic leading to the use of normal classrooms also demanded programs which were realistic in terms of current physics teaching practices. In order to achieve this instructional realism, all of the printed student text materials available for the Victorian grade 11 physics course which sold well (and, by implication, were used relatively widely) were inspected. Two were selected. These were judged to differ to the greatest extent in the emphasis given to external connections for Newtons Laws. Not surprisingly, both gave emphasis to the internal connections involved in Newtons Laws. The material which gave minimal emphasis to external connections (hereafter termed the Narrow program) was a linear program with a strong focus on solution of standard forms of Newton's Law problems. The alternative program gave substantial emphasis to external connections (hereafter the Broad program), that is, to attempts to establish links between the concepts of Newtons Laws and existing knowledge/experience. Strategies used in this attempt included the relating of relevant physics to common experiences (football, cricket, bicycle riding, etc.), the use of cartoons and cartoon strips, the use of human stick figures pushing real objects to provide summaries, the inclusion of historical odds and ends, and the provision of laboratory work and film. By comparison with the Narrow program there was considerably less emphasis on problem solution.

To ensure that the two programs did not differ in physics content presented they were given to a panel of five experienced teachers of high school physics. Some minor adjustments were made so that there was unanimous agreement about the equivalence, in terms of physics content, of the two programs.

The judgments of these same five teachers were used in the construction of a near and far transfer performance test. They were given a pile of items either taken from externally set Victorian grade 11 physics exams or written by the present author, and asked to sort these into five categories. All items classified identically by all five teachers into the first four categories formed, respectively, the one near transfer scale and the three far transfer scales of the performance test. The criteria given to the judging panel were: "1. Problems requiring the use of the basic formula taught in the learning programmes, both directly and transformed algebraically" (these formed the Near Transfer scale), "2. Problems which present a complicated-looking situation which could be solved quite easily if students would take a moment to think and/or problems asking about the formula or the variables contained in it rather than problem solutions" (far transfer-Formula Understanding), "3. Problems which, although very similar to Group 1, have no answer because the information given is inconsistent or insufficient" (far transfer-No Answer), "4. Problems requiring the application of what has been learned to new situations and which represent the sorts of final outcomes you desire from your teaching" (far transfer-Classroom Far Transfer), and "5. Does not fit any of the above groups" (these were discarded). Given the concern with real instructional settings in the study, the Classroom Far Transfer scale was of particular interest. The transfer test was given immediately after completion of the learning programmes. A long-term retention test was not possible because students went on to study related material (Work and Energy).

Three stimulus words were used on the WA/CP test. These were <u>force</u> (selected as a concept for which students were likely to have an existing relevant cognitive structure derived from experience rather than formal instruction), <u>velocity</u> (a concept with an existing relevant cognitive structure derived from instruction, as all students completed a study of kinematics prior to this study), and <u>mass</u> (a

unlikely to exist). Of these three, force is both the concept most central to the issues of explanation of motion which are encompassed by Newton's Laws, and the concept of particular importance in the considerations of internal and external connectedness. The later importance arises from it being the concept most likely to have associated with it relevant prior knowledge/experience which could provide the basis of links of the form of external connections. For these reasons, it is force WA/GP data alone which is reported here.

Because of concern with changes in aspects of cognitive structure which result from instruction, the WA/GP test was given both pre- and post-instruction.

Results

Table 1 gives the pre- and post-test means on WA/GP force, internal and external connections, for the two instructional groups. Where the differences between group means are significant at .05 (t-test for independent samples) this is indicated in Table 1.

Insert Table 1 about here

These data suggest that the two instructional forms have had the predicted effects on the aspects of cognitive structure which were probed. After instruction there was little difference between the two groups in mean numbers of internal connections, but the Broad group had a significantly larger mean number of external connections. This differences between the groups, but the general trends apparent in the data are consistent with the emphases in the learning programs.

The mean scores of the two groups on the post-instruction performance test are shown in Table 2. For three of the four scales, the means of the two groups are consistent with the previously argued likely effects of the two instructional forms. There is minimal difference in performance on the near transfer scale, and significant differences on two of the far transfer scales. These data are displayed in Figure 1 with the error bars around each plotted mean being the limits of mean $\pm$ one standard error of the mean. This display shows clearly the rather substantial differences in performance on two of the scales.

Insert Table 2 about here

Insert Figure 1 about here

The absence of difference between means on the third far transfer scale (Formula understanding) is difficult to interpret. There seem to be two possible explanations. One involves the forms of the two modes of instruction. As was outlined earlier, the concern with realism in these modes in effect has resulted in a blurring of the differences between them, relative to the Mayer, Greeno, et al. forms. The second possibility involves the nature of the formula ma) by comparison with that involved in much of the Mayer, Greeno work (binomial distribution). This made the construction of questions for the Formula understanding scale somewhat more difficult.

These performance differences are quite consistent with the trends in the WA/GP _force_ data. The aspects of cognitive structure which are probed by the WA/GP test -- internal/external connectedness -- have been argued to be of particular importance to the forms of performance involved in near/far transfer. The greater external connectedness in _force_ cognitive structure amongst the Broad group, on this interpretation, has resulted in superior performance on far transfer problems involving the concept force. Further, similar near transfer performance can be attributed to similar internal connectedness.

This issue of the validity of the relationship Instruction → Cognitive Structure → Performance was explored more directly by the use of path analysis -- a method of showing direct effects in a set of hypothesized causal relationships.

The following strategy was adopted for the application of path analysis to the data. Initially, an hypothesized causal model involving pre- and post-test WA/GP measures, instructional group (as a dummy coded variable), and performance was established. As already suggested, the WA/GP measures used were those obtained from the stimulus _force_. The performance scale used was the Classroom Far Transfer scale. This was chosen both because the abilities assessed by this scale were important abilities according to the panel of performance differences which were attributable to instructional differences existed for this scale. The form of the hypothesized causal model is shown in Figure 2.

Insert Figure 2 about here

This set of causal relationships is largely defined by the temporal sequence of the variables, e.g. pre-test WA/GP can logically be argued to have causal effect on post-test WA/GP, but the converse is absurd. Pre-test WA/GP and Treatment group, as givens at the beginning of the study, are represented as exogenous variables in Figure 2. The hypothesized direct effect of Pre-test WA/GP on Performance would seem likely to be small. It appeared very probable that the effect of Pre-test WA/GP on Performance would be mediated by Post-test WA/GP, i.e. the causal chain would be Pre-test WA/GP → Post-test WA/GP → Performance. On the other hand, the hypothesized direct effect of Instructional Group on Performance was likely to exist, as the WA/GP test purports to assess only one relevant aspect of cognitive structure. Hence this direct path shown in the model can be conceptualized as representing the effect of Instruction on other relevant aspects of cognitive structure, which in turn have effect on performance.

Separate full models were established for internal and external connectedness in <u>force</u> cognitive structure. Reduced models were then formed by omitting all causal paths with path coefficients less than for deciding what is or is not a negligible value for a path coefficient (Heise, 1968, p. 61). The extent to which the reduced model validly represented the data was then assessed by comparing the correlation coefficients derived from the reduced model with the correlations obtained from the original data.

Given the theoretical considerations underlying the study, differences between the reduced models for internal and external connections were expected. If the observed performance differences were in fact substantially attributable to the development of greater external connectedness in force cognitive structure in the Broad group students, then the reduced model including WA/GP external connections should show the effect of Instruction on Performance to be substantially mediated by the measure of post-test external connectedness. On the other hand this same argument leads to the prediction that the measure of post-test internal connections would have little such mediating effect on the Instruction → Performance relationship.

The full and reduced path models containing measures of internal and external connectedness in force cognitive structure are shown in Figures 3 and 4 respectively. The original correlations between variables in the models, the 95% confidence limits for those correlations, and the correlations calculated from the path coefficients for the reduced models are shown in Table 3. Because of the number of subjects involved in the study (67), the 95% confidence limits are of little use as a means of judging the adequacy of the correlations fall within these limits. The range encompassed by the limits is large. Direct inspection of the original and calculated correlations seems more appropriate. This suggests that the reduced models are in fact valid simplifications of the original data.

Insert Figures 3 and 4 about here

Insert Table 3 about here

The reduced models (Figure 3b and 4b) exhibit the trends which have been argued to be required if the relationships between instructional forms, development of aspects of cognitive structure, and performance are those hypothesized above. The measure of external connectedness has substantially mediated the effect of instruction on performance, whilst the measure of internal connectedness has not.

A Summary Discussion

Two general conclusions can be drawn from the preceding data and analyses. Firstly, it has been demonstrated that particular aspects of cognitive structure, which are logically related to particular instructional emphases and forms of post-instruction performance, do in fact play a mediating role in the effect of instruction on performance. This is a result of significance from the perspective of research. Secondly, it has been shown that hypothesized effects of previously shown to exist under under laboratory conditions for a particular subject domain, also exist in more normal learning conditions and for another subject domain. This is a result of instructional significance. It suggests that instructional strategies that overtly seek to foster external connections in the cognitive structures of students will increase performance on far transfer performance tasks. Further, given the general equivalence of the two instructional groups in terms of internal connectedness in cognitive structure and near transfer performance, this far transfer performance superiority does not have to be at the expense of the near transfer performance.

It is important to note that the two learning programs differed in emphasis given to external connections; it is not suggested that the Narrow program gave no emphasis to external connections. In fact it can be argued that a total absence of external connections in instruction is a logical impossibility. Given the presently widely accepted view that individuals actively generate and extract their own meaning from communications, totally internal connectedness in cognitive structure could only be achieved if individuals made no attempt to link in anyway to existing cognitive structure.

The idiosyncratic nature of meaning and linking with existing knowledge has other important implications. For example, it is not possible to prescribe all appropriate external connections in an instructional sequence. Different individuals will require different prompts to make such links. As a consequence, a tight and description of the external connections presented in the Broad program used in this research has not been attempted. Rather, the rationale for the Broad program could be described as an attempt to provide a wide range of what could logically be argued to be potential external connections for many students. Finally, another logical consequence of the idiosyncratic generation of meaning is that some learners will form inappropriate external connections, leading to a distorted and incorrect meaning being attached to new learning. There is much evidence of this phenomenon in current research in science learning (e.g. Champagne et al., 1980; Gunstone & White, in press).

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Table 1: Mean response (internal and external connections) to WA/GP force on pre- and post-test, by group

	Broad group (n = 35)	Narrow group (n = 32)	Significance of difference
Internal connections:			
pre-test	0.71	1.28	$p < .05$
post-test	2.23	2.47	-
External connections:			
pre-test	4.00	3.19	-
post-test	5.83	4.19	$p < .001$

Table 2: Mean scores on the four scales of the performance test, by group.

Scale (number , items)	Broad group	Narrow group	Significance of differenc
Near transfer (8)	7.09	7.38	-
Far transfer:			
Formula understanding (8)	3.23	2.81	-
No answer (3)	1.94	1.00	$p < .001$
Classroom for transfer (11)	5.37	3.53	$p < .01$

(In each of the following tables, the top line of the cells containing data is the original correlation between the variables indicated, the numbers in parentheses are the 95% confidence limits for the original correlations (n = 67), and the third line is the correlation generated by the reduced model. Where a pair of variables were exgenous, with the original correlation being taken as the correlation generated by the reduced model, this is indicated.)

(a) For model containing internal connectedness measure

	Instructional Group	Post-test int. conn.	Performance
Pre-test int. conn.	(exogenous variables)	.538 (.689, .342) .538	-.035 (.212, -.273) -.005
Instructional group		-.099 (.145, -.331) -.135	.327 (.526, .094) .322
Post-test int. conn.			.117 (.347, -.127) .064

(b) For model containing external connectedness measure

	Instructional Group	Post-test ext. conn.	Performance
Pre-test ext. conn.	(exogenous variables)	.359 (.522, .130) .358	.231 (.446, -.010) .171
Instructional Group		.467 (.636, .255) .467	.327 (.526, .094) .327
Post-test ext. conn.			.461 (.631, .248) .461

Figure 2. Plot of mean performance on the four scales of the performance test, by group

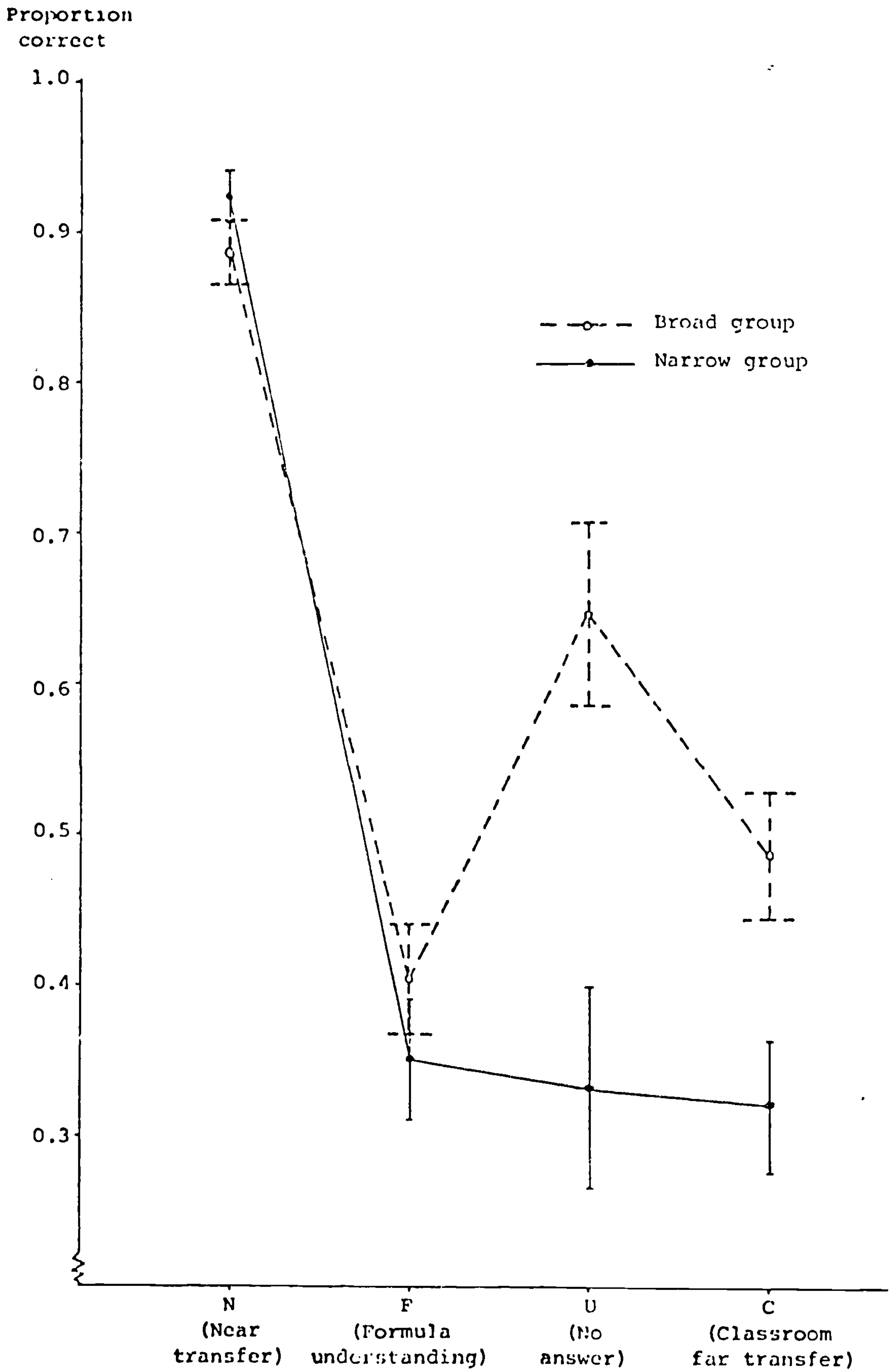


Figure 2: The basic structure of the models to be investigated.

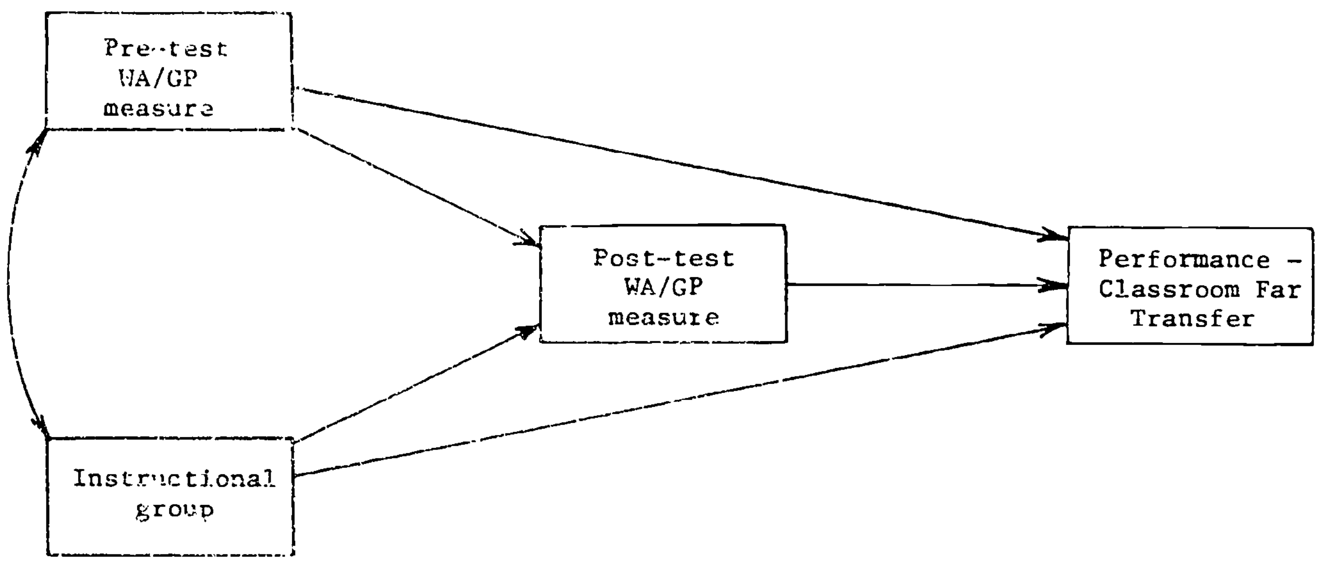
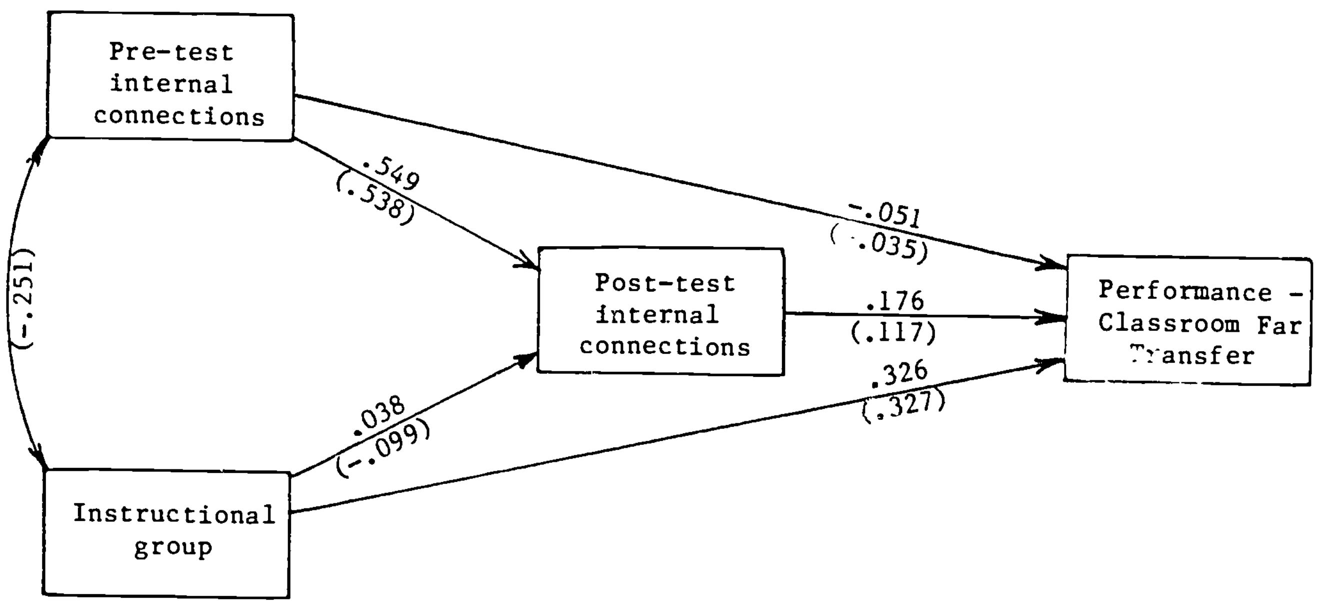


Figure 3: Path diagrams for models containing <u>force</u> internal connections.

(a) Full model (figures above paths are path coefficients, those in parentheses below are correlations)



(b) Reduced model (all paths with coefficients less than 0.1 deleted)

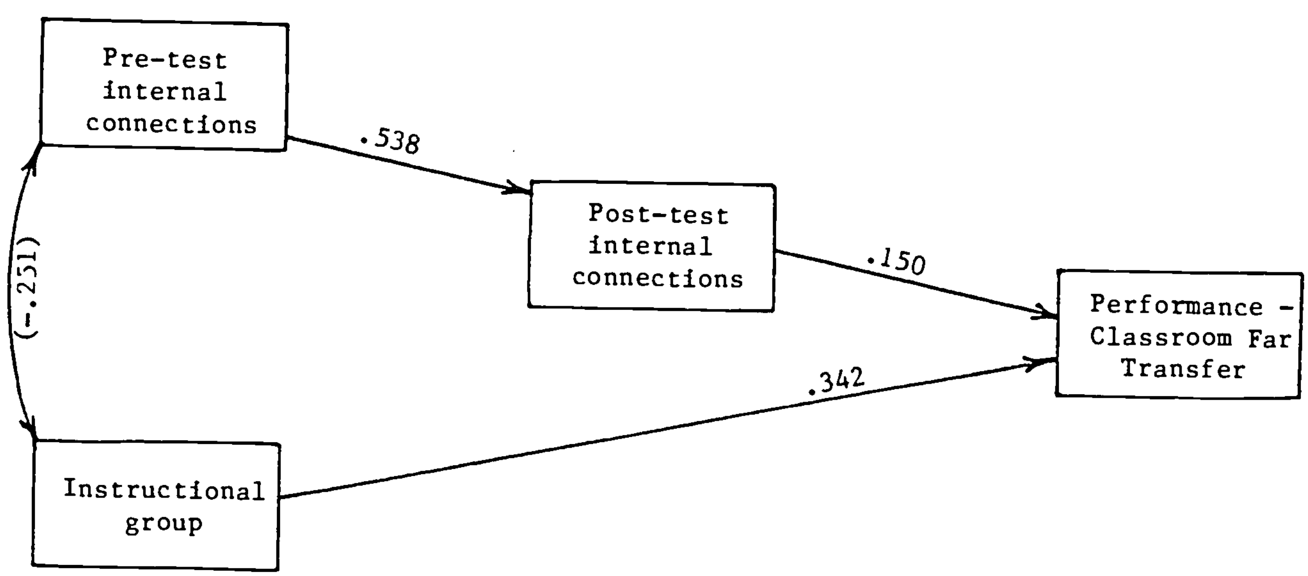
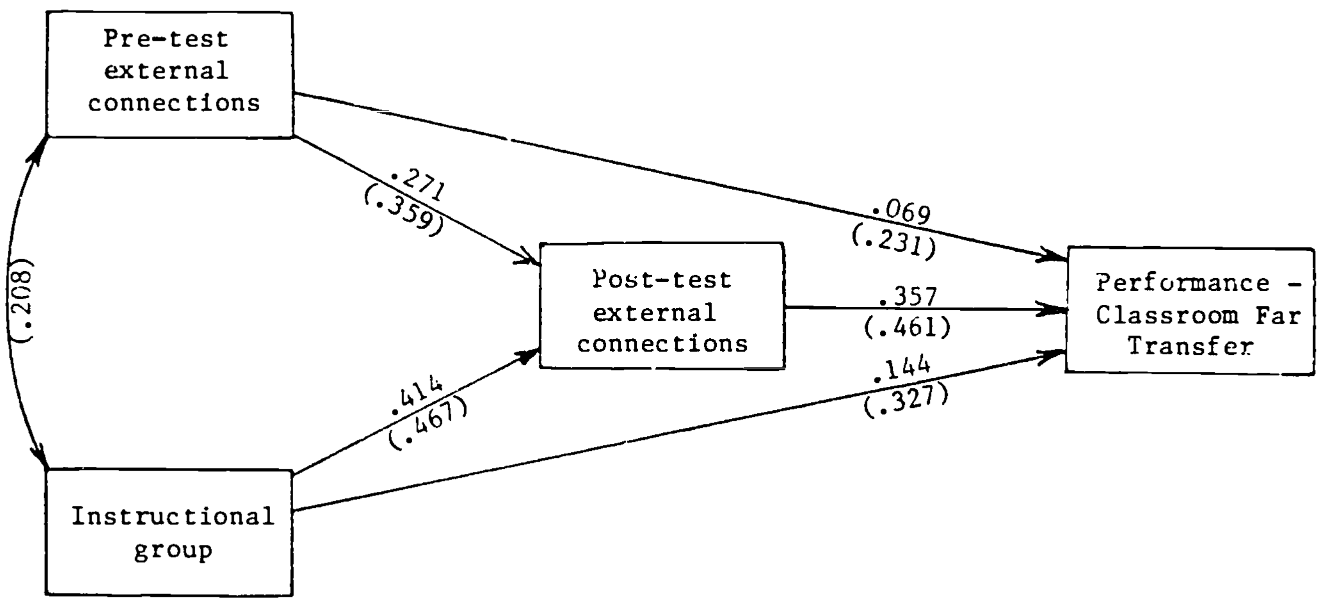


Figure 4: Path diagrams for models containing <u>force</u> external connections.

(a) Full model (figures above paths are path coefficients, those in parentheses below are correlations)



(b) Reduced model (al.. paths with coefficients less than 0.1 deleted)