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AUTHOR	Sternberg, Robert J.
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ABSTRACT

Two influential theories of intellectual development are reviewed and analyzed: the psychometric framework, based on the factorial composition of intelligence, and the Piagetian model, based on assimilation and accomodation through four stages of intellectual development. A third concept is the componential theory of intelligence, based on information processing models, and consisting of two basic units of analysis, the component and the metacomponent. The component is described as an elementary psychological process which operates on internal representations of objects on symbols; these components are encoding, inference, mapping, application, justification, and response. A metacomponent is described as a higher order psychological process which controls processes related to executing components; metacomponents consist of component selection, representation selection, strategy selection or planning, strategy monitoring, speed-accuracy tradeoff decisions, and solution monitoring. Conclusions were made, based on research using parochial school children in grades 2, 4, and 6 and college level adults: (1) that children show increased use of exhaustive information processing as they grow older; (2) older children are generally less willing to surrender accuracy for speed; and (3) older individuals are more consistent in applying a strategy to problem solving, although there is no evidence of a general strategy shift in time for any age group. Bibliographical references are appended. (MH)

The Development of Human Intelligence

Robert J. Sternberg

Yale University

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Send proofs to Robert J. Sternberg
Department of Psychology
Yale University
Box 11A Yale Station
New Haven, Connecticut 06520

The Development of Human Intelligence

Developmental psychologists seek to understand the psychological bases for the changes in behavior that ensue as people grow older. Everybody knows that children become more intelligent with increasing age: As they grow older, children become able to do more things, and to do most of the things they do, better. What is not obvious is why these changes in behavior take place. The present article deals with the sources of developmental change. The article will first review two theoretical frameworks for understanding the development of human intelligence that have been highly influential in the past, and then present a framework that is believed to possess certain advantages over its predecessors.

Previous Theoretical Frameworks for Understanding the Development of Human Intelligence

A number of theoretical frameworks have been proposed for understanding the development of intelligence. Two of these frameworks have been particularly influential both historically and in their impact upon contemporary research. These two frameworks are the psychometric and the Piagetian, each of which will now be considered briefly.

The Psychometric Framework

The psychometric framework for understanding the development of intelligence is usually traced back to the work of Alfred Binet and his colleagues in France (Binet & Simon, 1905a, 1905b, 1905c, 1908), and subsequently, to the work of Lewis Terman and his colleagues in the United States (Terman & Merrill, 1937, 1960). Their psychometric framework sought to understand the development of intelligence by analysis of the increasing ability of children of successively greater ages to solve relatively complex problems requiring skills of the sort encountered in everyday experiences. In much of the psychometric literature, three concepts have been central to analyzing intelligent performance. The first concept, chronological age, refers simply to a person's physical age from time of birth. The second concept, mental age, refers to a person's level of intelligence in comparison to the "average" person of a given age. If, for example, a person performs at a level comparable to that of an average twelve-year old, the person's mental age will be twelve, regardless of his or her chronological age. The third concept, intelligence quotient, or IQ, traditionally has referred to the ratio between mental age and chronological age, multiplied by 100. A score of 100 signifies that mental age is equivalent to chronological age. Scores above 100 indicate above average intelligence, scores below 100, below average intelligence.

For a variety of reasons, the concept of mental age has proven to be something of a weak link in the psychometric analysis of intelligence. First, increases in mental age seem to stop at about the age of 16. The interpretation of the mental age concept above this age thus becomes equivocal. Second, increases in mental age vary nonlinearly with chronological age even up to the age of 16. The interpretation of mental ages, and of IQ's computed from them, may therefore vary for different chronological ages. Third, the unidimensionality of the mental age scale seems to imply a certain sameness over age levels in the concept of intelligence--a sameness that the contents of the tests do not bear out. Infant tests, for example, measure skills entirely different from those measured by tests for adolescents and adults. Moreover, correlations between performances on the two kinds of tests are usually quite meager. For these and other reasons, IQ's have tended, in recent years, to be computed on the basis of relative performance within a given age group: One's performance is evaluated relative only to the performance of others of the same age. Commonly, scores have been standardized to have a mean of 100 and a standard deviation of 15 or 16. These "deviation IQ's" have been used in much the same way as the original "ratio IQ's," although in spirit they are quite different. In fact, the deviation IQ's are not even quotients at all!

Whatever its usefulness as a descriptive construct, <u>mental age</u> is of little usefulness as an explanatory construct: It may describe increases in level of performance on intellectual tasks, but it certainly does not explain them. Psychometricians have thus been led to seek alternative ways of conceptualizing the development of intelligence. One such way has been through the model of factor analysis. Factor analysis is a statistical tool that seeks out common sources of variation among people, and identifies these common sources as unitary psychological attributes, or factors. Different theorists have proposed differing sets of factors to account for the structure of mental abilities.

The earliest view, that of Spearman (1927), is that intelligence comprises a general factor (<u>g</u>) common to performance on all of the various tests that are used to measure intelligence, plus a specific factor (<u>s</u>) involved in performance on each individual test. The number of specific factors, therefore, is equal to the number of tests. A later view, that of Thurstone (1938), is that intelligence is best described as comprising a set of approximately seven primary mental abilities, namely, verbal comprehension, verbal fluency, number, spatial visualization, perceptual speed, memory, and reasoning. On this view, any general factor that exists must be viewed as "second-order," existing only by virtue of correlations between the primary mental abilities. A relatively recent view, that of Guilford (Guilford, 1967; Guilford & Hoepfner, 1971), is that intelligence comprises as many as 120 factors, each of which involves an operation, a content, and a product. There are five kinds of operations, six kinds of products, and four kinds of contents, yielding the 120 (5 x 6 x 4) factors. Examples of such factors are cognition of figural relations, measured by tests such as figural (abstract) analogies, and memory for semantic relations, measured by tests requiring recall of semantic relationships such as "gold is more valuable than iron." Probably the most widely accepted view among factor theorists today is a hierarchical one, which has been proposed by several theorists in somewhat differing forms (e.g., Burt, 1940; Snow, 1978; Vernon, 1971). On Vernon's view, for instance, intellectual abilities comprise a hierarchy, with a general factor (g) at the top; two major group factors, verbal-educational ability (v:ed) and spatial-mechanical ability (k:m) at the second level; minor group factors at the third level; and specific factors at the bottom.

Few of the major factor theorists of intelligence have given serious consideration to developmental questions, with the result that the original factor theories had little to say about the development of intelligence. Most of the developmental work on intelligence as conceived from a psychometric point of view has been done by disciples of the original factor theorists. This work has tended to emphasize empirical issues more than theoretical ones. Nevertheless, at least four sources of intellectual development can be inferred from the factor model.

First, the identities or relative importances of the various factors of intelligence can change with age. Bayley (1958, 1968), for example, has suggested that different factors are operative at different age levels, and that the relative contributions of the different factors also change with age. A sensori-motor factor dominates behavior during the first year of life; a factor of persistence and goal-directedness dominates behavior during the second and third years of life; what Bayley refers to as true "intelligence" does not even appear at all until eight months of age. Eventually, however, this factor dominates the others. Overt performance on this factor is characterized by the ability to learn and engage in abstract thinking. As a second example, consider the role of the perceptual speed factor at different ages in Thurstone's theory. Although this factor is claimed to be involved in intelligent behavior at all ages, its relative importance changes. Whereas the test batteries used to measure intelligence at younger age levels include tests of perceptual speed, the test batteries used to measure intelligence at older age levels do not include such a test (Thurstone & Thurstone, 1962).

Second, the number of factors, or differentiation of factors, can change with age. Garrett (1946), for example, has suggested that abilities become more differentiated with age, resulting in a progressive decrease in the importance of the general factor (*g*) with increasing age. A hierarchical view of intelligence deals particularly well with this source of intellectual development, since the hierarchy of abilities can be viewed as becoming increasingly more differentiated or ramified with age: Both the breadth and the depth of the hierarchy may change as individuals grow older.

Third, the tests measuring performance and hence the behaviors characterizing a given factor can change with age. In the SRA Primary Mental Abilities battery, for example, spatial ability is measured in one way in the battery for grades 4 through 6, and in another in the batteries for higher grades. In the battery for the earlier grades, children must indicate which of four geometric forms will form a square when combined with a given form. In the battery for the later grades, children must indicate whether each member of a set of geometric forms is a rotated version of a given form, or a rotated version of the given form's mirror image.

Fourth, absolute amounts of the abilities represented by various factors can increase with age, possibly at different rates. In some cases, one ability may increase while another may simultaneously decrease. Horn and Cattell (1967), for example, found that performance on tests of "crystallized" general ability, such as vocabulary, continues to increase throughout the age range from 14 to 16 years; performance on tests of "fluid" general ability, such as abstract reasoning, monotonically decreases throughout the same age range. Wechsler (1958) has found declines in both verbal and performance scale scores after about the mid-twenties, but decline in performance scores occurs at a faster rate than decline in verbal scores.

The factor model is obviously able to provide some kind of account of intellectual development. Yet, the influence of the factor model has declined in recent years. There seem to be several reasons for this decline, not all of them involving exclusively developmental considerations (Sternberg, 1977b, 1978c).

First, and most important from a developmental point of view, the factor model provides no mechanism of transition between one level of performance and another: Although it can provide information regarding performance at each of two respective levels, it does not provide information regarding the way in which the first kind of performance gave way to the second. Thus, for example, one is given no clue as to how to account for increases that occur in amounts of abilities represented by factors, or as to how to account for increases in numbers of factors.

Second, the model has not been successful in explicating the processes involved in intelligent behavior. Intelligent behavior presumably reflects outcomes of mental processes, but factor analysis leaves one with little or no idea of what these processes are. Factor analysis is a structural model, and its strength is in providing a picture of how abilities are organized. But an account of structure without process is incomplete, both within and between age levels.

Third, factor analysis has certain statistical weaknesses that render the interpretation of factor-analytic results equivocal. The inferential machinery for disconfirming factorial solutions is not well-developed, making it difficult to distinguish between alternative factor-analytic models. Moreover, factorial solutions are subject to arbitrary rotation in space. Imagine a "factor space" containing a set of axes and points having various coordinates along those axes. The interpretation of the points (usually tests) will obviously depend upon their spatial locations with reference to the axes. But the axes are mathematically arbitrary: Only the placement of points in the space is fixed. As a result, different theories, corresponding to different placements of the axes in the factor space, can be viewed as accounting for the data equally well, at least from a mathematical point of view. Attempts to use methods other than factor analysis to distinguish among factor theories that differ from each other only by the placement of axes in a factor space have been scarce, and not particularly illuminating.

To conclude, the factorial model of intelligence and its development is of some, but limited, usefulness. Its strength seems to be in its ability to provide a picture of how abilities (at some level of analysis) are organized at various age levels. Its weaknesses lie in its inability to provide a unique picture, in its inability to account for dynamic information processing, and in its failure to specify how transitions occur. An alternative framework for conceptualizing the development of intelligence, that of Piaget, seems to fare better on all of these counts.

The Piagetian Framework

Piaget (1950; 1952; see also Flavell, 1963) views the development of intelligence in terms of a series of stages representing discrete levels of intellectual development. There are four successive stages in the theory.

The first stage, lasting roughly from 0 to 2 years, is referred to as the sensorimotor stage. Children in this stage interact with the environment by means of overt sensorimotor actions, like grasping and sucking. Sensations obtained through vision and audition are of prime importance. The stage is divided into a series of six substages. During the first substage, lasting from birth to about one month of age, the child uses and further develops the reflexes with which it was born. During the second substage, lasting from about one to four months, the baby learns to repeat pleasurable actions that the first time (or several times) may have been executed only by chance. The child's exploration of the environment also reaches a level of selectivity that was not apparent during the first substage. During the third substage, lasting from about four to ten months, the child shows some intentionality in his or her actions, and begins to understand cause and effect between actions and their results. The concept of object permanence also begins to develop: If a ball in motion disappears behind a screen, the baby shows signs of expecting its reappearance at the opposite end of the screen. During the fourth substage, lasting from about 10 to 12 months, clear intentionality emerges, and the baby instigates actions other than responses to things that first happened by accident. During the fifth substage, lasting from about 12 to 18 months, the child conducts experiments on the environment, systematically varying actions to see the effects of variation upon the outcomes of the actions. The concept of object permanence has also become fully developed. During the sixth and last substage, lasting from about 18 months to 2 years, the frequency of experimentation increases, and the systematicness in the experiments also increases. The child shows clear signs of what we call "thought," and begins to manipulate internal representations in ways that permit multistep actions to obtain desired outcomes.

The second stage, lasting roughly from 2 to 6 years of age, is referred to as the preoperational stage. Children learn during this stage to represent objects in primitive symbolic forms. The child at this stage is egocentric, viewing the world in terms of the self and the child's own experiences. The child is unable to see points of view other than his or her own. Reasoning is largely transductive--from specific to specific--and correlational. Thus, the child may appreciate systematic relations between pairs of occurrences, without appreciating the higher-order causes of these relations. The stage is called "preoperational" because it is almost as noteworthy for what children cannot yet do as for what they can do (at least according to the Piagetian view). Two skills that preoperational children lack, for example, are reversibility and class inclusion. Lack of reversibility means that the child cannot trace a reasoning process backward as well as forward. For example, if an experimenter pours all of the water from a tall, thin glass into a short, fat glass, the child will usually say that there was more water in the first glass than there is in the second glass; if the pouring process is then reversed, the child will say that there is more water in the tall, thin glass. Lack of reversibility results here in an inability to "conserve quantity." Lack of class inclusion ability means that the child is generally unable to find a principle common to a set of similar objects. Asked to classify objects according to a common principle, the child may be able to point out ways in which pairs of objects are related, but the principle of classification may differ for different pairs, rather than being common to the whole set of objects.

The third stage, lasting from roughly 6 to 12 years of age, is referred to as the concrete operational stage. It is probably the most widely studied of the four stages. The operations are designated as concrete because they are still tied to concrete objects. The capacity for abstract thought is not yet fully developed, although the ability to reason inductively is fairly well established. Children during this stage have acquired both reversibility and class inclusion. Reversibility is shown by their abilities to add and subtract, multiply and divide, and to conserve. Conservation of quantity (or volume) is demonstrated by the children's ability to recognize that a fat, short glass holds the same amount of water as the tall, thin glass from which the water was poured. Similarly, children will realize that regardless of the shape into which a ball of clay is twisted, the amount of clay remains invariant over the various shapes. Children learn to conserve number as well as quantity: They recognize that a row of coins with the coins two inches apart from each other holds the same number of coins as a row of coins with the same coins one inch apart from each other. Children during this stage also acquire the abilities to seriate and to make transitive inferences. The ability to seriate allows children to order objects along various dimensions--from short to tall, from light to dark, or from thin to fat. The ability to make transitive inferences enables a child to infer that if John is taller than Pete, and Pete is taller than Bill, then John is taller than Bill.

The fourth and last stage, beginning at the age of 11 or 12, is referred to as the stage of formal operations. The critical acquisition of this stage is the ability to reason abstractly, that is, without reference to concrete objects or events. Children become able to reason from the general to the specific (deductively), and thus to use the peculiar blend of inductive and deductive reasoning characterizing the methodology of scientific inquiry. During this stage, children acquire the ability to comprehend second-order relations of the kind used in reasoning by analogy. Thus, formal-operational individuals can understand not only relations between objects, but relations between relations as well.

Whereas the psychometric framework seemed to have no mechanism of transition between levels of intellectual development, the Piagetian framework has two well-formulated mechanisms--assimilation and accommodation. In *assimilation*, an individual incorporates an object (whether concrete or abstract) into an existing cognitive structure, if necessary, adapting the perceived properties of the object to fit the structure. In *accommodation*, the individual reverses priorities, adapting properties of the cognitive structure as needed to fit the object. Assimilation thus involves adjustment of the properties of the object; accommodation involves adjustment of the properties of the cognitive structure. Intellectual development is largely attributable to the fittings and refittings of objects to cognitive structures (and vice versa) that occur as a result of assimilation and accommodation. These fittings and refittings continue to occur throughout one's lifetime.

It would be difficult to overestimate the impact Piaget's theory has had upon thinking about intellectual development. Yet, the theory seems to have become somewhat less influential during the last several years. In part, this decline in influence can be attributed to the rethinking and revisionism that inevitably follow some years after any major breakthrough. But there seem to be more substantial reasons as well for the decline.

First, the explanatory value of the concept of a stage of intellectual development has been called into serious question (see, for example, Brainerd, 1978). On the one hand, the concept of a stage is useful because of the apparent emergence of groups of related behaviors that are qualitatively different from the behaviors that preceded them. On the other hand, the concept of a stage is vitiated by the clearcut development that occurs within as well as between stages. Piaget and his colleagues account for this within-stage development in two principal ways. The first is through the postulation of substages. The other is through the postulation of horizontal décalage, by which abilities such as seriation or transitivity are allowed to develop slowly rather than to appear all at once: Abilities permeate slowly through the various content domains to which they can be applied, rather than appearing in all of these content domains simultaneously. For example, seriation with sizes might precede seriation with shadings. The problem, of course, is that as the borders between stages are blurred, the usefulness of the stages as explanatory constructs decreases.

Second, although the stages may explain individual differences across childhood age levels reasonably well, they seem inadequate to explain individual differences beyond early adolescence, and particularly, between adults of approximately the same age. Differences in intellectual performance among adults remain striking, despite the fact that most of these adults can be presumed to be formal-operational. Either the stage construct is inadequate, or at least one additional stage must be postulated. Several attempts have in fact been made to postulate a fifth stage: Arlin (1975), for example, has proposed a fifth "problem-finding" stage, to be distinguished from the problem-solving stages that precede it. Case (1978) has suggested a fifth stage consisting of the newly developed ability to perceive relations beyond the second order, as would be required in the perception of an analogy between analogies (Sternberg & Conway, Note 1).

Third, certain aspects of the theory seem to be incorrect. Obviously, no theory will be correct in all its aspects. But some of the most fundamental tenets of Piagetian theory have been challenged in recent years, with apparent justification. An example of such a challenge is that of Trabasso

(Bryant & Trabasso, 1971; Riley & Trabasso, 1974; Trabasso, 1975) to the notion that transitivity is impossible before the stage of concrete operations. In a series of ingenious experiments, Trabasso and his colleagues have provided strong evidence that failure of preoperational children to solve transitive inference problems is due to memory rather than reasoning limitations. When memory demands are removed from the task, preoperational children do appear to be able to perform transitive inferences.

Fourth and finally, Piagetian theory seems to be far more applicable to the mathematical and scientific thinking of children (and particularly older children) than it does to their thinking in disciplines such as literature and history.[1] This bias in the coverage of the theory manifests itself in the tasks that have been investigated. Almost all of the tasks administered to concrete- and formal-operational children are logical and scientific in nature. A complete theory of intellectual development, however, would need to say more about the development of more intuitive forms of thinking than does Piagetian theory in its present form.

To conclude, the Piagetian model of intelligence and its development is of considerable usefulness. But its usefulness, like that of the psychometric model, is limited. Its strength seems to be in its detailed account of the development of scientific forms of thinking, and in its well worked out mechanisms for transitions between levels of development. Its weaknesses are in its limited applicability to non-scientific forms of thinking, in probable errors in the reasons postulated for certain behaviors, in its inability to account for individual differences among adults, and in certain weaknesses of the concept of the stage.

The strengths and weaknesses of the psychometric and Piagetian models are largely complementary. A number of investigators have responded to this apparent complementarity by attempting to integrate the two models. Many of these attempts have taken the form of Piagetian tests of intelligence that resemble in form but not in content the traditional psychometric tests. A major goal of such research has been to determine whether a Piagetian type of test considered in conjunction with a psychometric type of test (based upon Binet's) might provide increased theoretical understanding and practical prediction of intellectual development. An example of such research is reported by Tuddenham (1970). Investigators have typically found that the Piagetian tests provide significant prediction of academic performance, but prediction at a level lower than that provided by good standard psychometric tests. When the two types of tests are considered in conjunction, the increase in level of prediction is sometimes statistically significant, but it is rarely practically significant. The general conclusion seems to be that at least from a practical point of view, Piagetian tests do not have a great deal to offer.

The Componential Framework for Understanding the Development of Human Intelligence

In recent years, a number of approaches to studying the development of intelligence have been spawned by an information-processing paradigm borrowed from computer science (see Miller, Galanter, & Pribram, 1960). As this paradigm has come to dominate cognitive psychology, it has diverged further and further from the original computer metaphor on which it was based. Although many adherents to the paradigm still remain quite close to the computer metaphor in their thinking (for example, the "Carnegie-Mellon School" led by Newell and Simon), most adherents to the paradigm use the computer metaphor only as a background stimulant to their theorizing.

The dominant goal in the information-processing approaches has been to understand how children and adults process information, and how the information they process is represented in memory. Many of these approaches have attempted to apply theoretical and methodological refinements derived from the information-processing paradigm to improve upon, or substantially revise, Piaget's basic formulations (e.g., Case, 1974a, 1974b, 1978; Gelman & Gallistel, 1978; Osherson, 1974; Pascual-Leone, 1970; Siegler, 1976, 1978). The approach proposed here, called "componential analysis" (Sternberg, 1977b, 1978a, 1978b, 1978c, 1979), differs from most of these approaches in that is has been more heavily influenced by the psychometric framework than by the Piagetian one. Its basic orientation, however, like that of these other approaches, derives from information-processing psychology.

The remainder of this article will be divided into three parts. First, an outline of the basic theory of intelligence will be presented. This outline of the theory applies to all individuals, regardless of age. Next, the theory of intellectual development will be described, and examples will be given of how the theory elucidates the changes in intelligent behavior that occur as children grow older. Finally, consideration will be given to how it might be possible to combine the three approaches to intellectual development considered in this article into a single, unified framework.

Theory of Intelligence

Basic units of analysis. In the componential theory of intelligence, there are two basic units of analysis, the component and the metacomponent. Generally speaking, components are used to solve problems, and metacomponents are used to decide how problems will be solved in the first place. Children of varying ages differ in what components and metacomponents are available to them, and in how effectively they use the components and metacomponents available to them.

A component is an elementary psychological process that operates upon internal representations of objects or symbols (Newell & Simon, 1972). The process may translate a sensory input into a conceptual representation, transform one representation into another one, or translate a conceptual representation into a motor output (Sternberg, 1977b). According to a subtheory of intelligence I have proposed, which I call a "unified componential theory of human reasoning," intelligence comprises a relatively small number of components. Various combinations of these components account for performance on the variety of problems commonly used to assess intelligence. Consider, for example, the components involved in reasoning by analogy.[2] Suppose one's goal is to solve the analogy, GENIE : MAGIC CARPET :: WITCH : (a. BROOMSTICK, b. CAULDRON). How might an individual go about solving this problem, and others like it? The following list of components seems to be sufficient for analogy solution:

1. Encoding. First, an individual may encode (at least the first two) terms of the analogy. During encoding, the individual retrieves from long-term memory attributes of each term that may possibly be relevant later in solution of the analogy. For example, the individual may recognize that a genie is a supernatural being who serves the master who summons him, usually via a magic lantern; and that a magic carpet is a supernatural mode of air transportation. Failure to encode basic facts about each analogy term will often lead to an erroneous solution to the analogy.

2. Inference. Next, an individual may infer one or more relations between the first two terms of the analogy. The number of possible relations that might be inferred is often extremely large; it is constrained only by the attributes that are encoded for each term at some point during problem solution. In the example, the individual might infer that a magic carpet is the mode of transportation a genie uses to transport himself from one place to another.

3. Mapping. After inference, the individual may map the relation between

the first and second halves of the analogy, carrying over from the first term (in the example, GENIE) to the third term (in the example, WITCH) the relation for which an analogy is sought. In this case, both terms refer to supernatural beings. The more highly related the first and third terms are, the easier it will be to carry out this mapping. More creative analogies generally are characterized by larger distances between the first and third terms: A relation is perceived between two concepts that do not bear obvious relationships to each other.

4. Application. Next, the individual may apply from the third term (in the example, WITCH) to each of the answer options (in the example, BROOMSTICK and CAULDRON) the various relations that were inferred from the first term to the second, as mapped to the third. In the example, a witch can fly on a broomstick, but not on a cauldron.

5. Justification. An analogy can be considered "ideal" if all of the relations inferable between the first two terms are applicable between the last two terms. Such analogies are relatively rare. In the example, a magic carpet is not uniquely associated with genies as a means of conveyance, whereas a broomstick seems to be uniquely associated with witches. Because in most naturally occurring analogies no one answer is ideal, the individual may justify one completion as nonideal, but superior to other available completions. In the example, BROOMSTICK is clearly a better completion to the analogy than is CAULDRON, even though neither completion is precisely related to WITCH in the way that MAGIC CARPET is related to GENIE.

6. Response. Finally, the individual responds with his or her answer, in the example, BROOMSTICK. The response may be communicated orally, in writing, or by some other means, such as by pressing one of several buttons on a button panel.

A _metacomponent_ is a higher-order psychological process that controls matters relating to the execution of components. Consider the metacomponents that would be needed for solution of an analogy, or for most kinds of problems requiring intelligent performance:

1. _Component selection_. What components should be used in problem solution, given the total set of components available?

2. _Representation selection_. What representation or representations should be used in problem solution? People can presumably represent information in a variety of different formats (as linguistic attributes, as locations in a multidimensional semantic space, as members of clusters, to name a few). A given component may be able to act upon one or more of these formats.

3. _Strategy selection or planning_. Which of the available strategies should be used, or if no appropriate strategy is available, what strategy can be formed that will satisfactorily solve the problem? Issues to be decided include such things as the point or points during the solution process at which various components should be executed; how to use information gathered from execution of one component to guide execution of another component; and when to stop execution of one component and move on to execution of another. This last issue is particularly important, since, as we saw, the number of possible encodings or relations that might be processed is extremely large, and some rule must be instituted to terminate what could be almost indefinite execution of a component.

4. _Strategy monitoring_. Once a strategy is chosen, its continued use throughout the duration of problem solving may or may not be desirable. As more experience is gained with a particular type of problem, a more flexible or efficient strategy may emerge, which may or may not use exactly the same components and representations. Hence, the components and representations must

be monitored as part of the strategy monitoring process.

5. Speed-accuracy tradeoff decision. A decision must be made as to just how important speed and accuracy are relative to each other. This decision is not independent of others, since the choice of strategy may affect speed-accuracy tradeoff, or vice versa.

6. Solution monitoring. As a problem is being solved, the individual needs to maintain some state of awareness regarding how well problem solution is going. If it is going well, then things can proceed according to the plans set up by other metacomponents. If things are not going well, previous metacomponential decisions may have to be remade, and the solution process may have to backtrack, or start over essentially from scratch.

These metacomponents are probably not the only ones involved in the solution of analogies or other problems requiring intelligence. Nor is it even clear at this point that each is a separate metacomponent. Although my colleagues and I have conducted fairly extensive research on components of reasoning, we are only starting to investigate metacomponents, and hence we know much less about them. The present list seems like a reasonable start, however.

Structure and content of the theory.[3] The theory of reasoning proposes a relatively small number of basic psychological components and metacomponents, and makes the empirically testable claim that these various components and metacomponents combine in various ways to make possible the solution of a wide variety of reasoning problems. Thus, the reason people who do well (or poorly) on some reasoning tasks tend also to do well (or poorly) on other reasoning tasks is that the tasks involve overlapping components and metacomponents. Components and metacomponents differ in their generality: Some are probably common to all of the various reasoning tasks one might consider; some are probably common to only a proper subset of these tasks, but to at least two such tasks; and others are probably specific to single tasks. Components and metacomponents of the first two kinds are obviously of greater psychological interest.

In order to see more clearly how tasks interrelate via components and metacomponents, consider a classification problem, where the individual's task is to indicate which of two (or more) answer options fits better with the terms in the stem of the problem. An example of such a problem is WITCH, GENIE, WARLOCK, (a. GENIUS, b. PHANTOM). In this problem, the individual may use five of the six components also used in the solution of analogies. The individual needs to encode the terms of the problem; infer what is common to the three terms in the stem (for example, that they are all supernatural beings); apply some or all of the relations inferred in order to determine which option possesses the same property or properties (a phantom is also a supernatural being); optionally, justify one of the options as imperfect, i.e., possessing only a proper subset of the inferred properties, plus, perhaps, some incongruent properties, but superior to the other option, i.e., possessing more of the inferred properties than the other option; and respond. The classification problem seems to require the same metacomponents as the analogy problem: The individual must select components, select a representation, select or plan a strategy, monitor the strategy, decide how to trade off speed for accuracy, and monitor his or her solution process. Other kinds of inductive reasoning problems would also require overlapping components and metacomponents, leading to the appearance of an "inductive reasoning ability."

Theory of Intellectual Development

In the componential framework for the development of intelligence, intellectual development is understood in terms of the components and metacomponents of information processing. The framework can best be elucidated by showing cognitive development in each of the components and metacomponents of information processing described in the preceding section.[4]

Consider first the basic methods used in an experiment to test componential and metacomponential development in analogical reasoning. Between 15 and 21 parochial-school children in each of grades 2, 4, and 6, and college-level adults, were timed as they solved analogies of the two forms shown in Figure 1 (Sternberg & Rifkin, 1979). Analogies of the first kind (referred to as schematic-picture analogies) contained terms varying in four binary attributes: hat color (white, black), suit pattern (striped, polka-dotted), hand gear (briefcase, umbrella), and footwear (shoes, boots). Analogies of the second kind (referred to as People Piece analogies) also varied in four binary attributes: height (tall, short), garment color (black, white), sex (male, female), and weight (thin, fat). Although the two types of analogies seem similar in many respects, they differ in one fundamental respect: Stimulus attributes in the first kind of analogy are separable, whereas those in the second kind of analogy are integral (Garner, 1970, 1974). In a stimulus with separable attributes, it is possible to have a null value on any one of the attributes and still to preserve the intactness of the stimulus: A null value on any one attribute means simply that the attribute is nonexistent. Consider the separable attributes in the analogy at the top of Figure 1. One could eliminate the hat, suit pattern, handgear, or footwear from a given schematic picture without destroying the intactness of the basic figure. In a stimulus with integral attributes, "in order for a level on one dimension to be realized, there must be a dimensional level specified for the other" (Garner, 1970, p. 354). For example, to portray the sex of a People Piece figure, one must draw the figure at some height and weight. Similarly, to portray a figure's weight, the figure must be drawn at some height, and vice versa. The importance of the difference between separable and integral attributes for information processing will become clear later.

Insert Figure 1 about here

Subjects were told to choose as their answer the option that was the same as and different from the third analogy term in the same way that the second term was the same as and different from the first term. Analogies were presented in 24 test booklets, each containing 16 analogies. Each booklet was timed for 64 seconds. Items within each of the 24 booklets were homogeneous in terms of the number of attributes varied from the first term to the second, from the first term to the third, and between the two answer options. Since identities of actual values on attributes varied across analogies, however, no two analogies were identical. Solution latency for items correctly answered was computed by dividing 64 (the number of seconds per booklet) by the number of items correctly completed in a given booklet. Latencies for all items answered and error rates were also computed. Response time is hypothesized to equal the sum of the amounts of time spent on each component. A simple linear model predicts response time as the sum across the different components of the number of times each component is executed (as an independent variable) multiplied by the duration of that component (as an estimated parameter). Parameter estimation was done by multiple regression, predicting response times from independent variables representing structural aspects of the analogy items.

Componential development. Figure 2 shows the average amount of time spent on problems of each content type at each grade level, and also partitions the overall response time into its components. The mathematical models upon which the estimates of component latencies are based differed across experiments and between grade levels for the People Piece analogies (in ways to be described in the next section). The values of R^2 (proportion of variance accounted for in the latency data) were .91, .95, .90, and .94 for the schematic-pictures in grades 2, 4, 6, and adulthood respectively; the values of R^2 were .82, .80, .86, and .89 for the People Pieces in grades 2, 4, 6, and adulthood respectively. It is worth noting that none of these models were "true models," in the sense of

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Insert Figure 2 about here
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accounting for all of the reliable variance in the data. The models did do quite well, however, and each model was the best of at least three alternative models considered.

1. Encoding. For schematic-picture analogies, encoding time was the longest component time at all levels except grade 4. For People Piece analogies, encoding and response times were confounded. Of particular interest is the curvilinear pattern of latencies for the schematic-picture stimuli: Encoding times first decreased, and then increased with increasing age. The confounded curve for the People Piece analogies is consistent with the possibility of such a pattern for encoding, although of course its existence cannot be demonstrated because of the confounding. Understanding of the curvilinearity must be sought at the metacomponential level, and hence further consideration of the finding will be deferred until the next section.

2. Inference. Inference and application times were confounded, and hence are presented in combined form. These times generally decreased across grade levels, as would be expected. Increases were statistically trivial. The times were relatively short, indicating that relational comparisons were performed quite rapidly in these very simple analogies.

3. Mapping. The mapping component was not used for the solution of schematic-picture analogies (see next section). It was used from grade 4 onward for the solution of People Piece analogies, and showed a monotonically decreasing pattern. These times were extremely low, suggesting that mapping, too, can be accomplished very rapidly in simple analogies.

4. Application. (See 2.)

5. Justification. Each analogy had an "ideal" solution, given the four attributes that were systematically varied for each content type. Hence, justification was not needed for analogy solution.

6. Response. Response component time decreased monotonically across grade levels for the schematic-picture analogies. It was confounded with encoding time for the People Piece analogies. The plotted curve is consistent with a monotone decrease, however.

If the patterns of component latencies make one thing clear, it is that they can be understood only through an understanding of the metacomponential decisions that largely control them. We therefore proceed to a consideration of these decisions.

Metacomponential development. We have not yet modeled metacomponential decisions and extracted latencies for them, although we are currently working on this problem (Sternberg & Salter, Note 4). We have been able to trace some metacomponential decisions over the course of development, however, and have acquired some understanding of why particular decisions are made at different points during development.

1. Component selection. A component process is considered to have been used in solution of a problem if its estimated latency (raw regression coefficient in a multiple regression) is significantly greater than zero. If the coefficient is not significantly greater than zero, then either (a) the process under consideration was not executed, (b) the duration of the process was too brief to be measured reliably, or (c) the duration of the process was constant across item types, and hence could not be separated from the regression constant (usually used to measure the duration of the response component). Parameter estimation procedures do not distinguish among these alternative explanations for a trivial parameter.

In the analogies research described above, the data suggested that encoding, inference, application, and response were used in solution of analogies by individuals of all age levels, and for analogies with both separable and integral attributes. Mapping appears not to have been used (or to have been executed extremely rapidly or to have been constant in duration across item types) at the grade 2 level, and to have been used at the higher grade levels only for analogies possessing integral attributes.

The fact that mapping was used in the solution of one type of analogy (with integral attributes) and not another (with separable attributes) suggests that the selection of this component for use in analogy solution can depend upon attribute type. Mapping is required only when attributes are "integrated," that is, perceived configurally rather than individually. It is not required when people consciously process each attribute separately, inferring the relation between a given attribute of the first term and the corresponding attribute of the second term, and immediately carrying over the relation from the third term to the fourth. The distinction between the two kinds of attributes and hence information processing applies to other kinds of analogies as well: Verbal analogies are processed integrally (with mapping), since individuals do not consciously extract attributes of words on a one-by-one basis. Geometric (abstract) analogies can be processed separably (without mapping) if perceptually distinct and distinctive attributes are used.

The fact that mapping was used in the solution of the analogies with integral attributes only by the older children (grades 4 and 6) and adults suggests that the component is unavailable or inaccessible to very young children. The use of mapping requires recognition of a second-order relation between two relations, that is, of the higher-order relation that links the relation between the first two analogy terms to the relation between the last two analogy terms. Previous research (Inhelder & Piaget, 1958; Lunzer, 1965) has suggested that second-order similarity relations of the kind needed for mapping do not develop until the formal-operational stage, which begins at about the age of 11 or 12 years. Thus, one might expect second-graders (mean age: 8) to lack the mapping component, and to seek to solve the analogies in a way that bypasses mapping. Separating the attributes on a one-by-one basis provides such a way. Fourth graders (mean age: 10) show the beginning of a mapping component. Since the children in this study were students in an upper-middle class, Jewish parochial school, one might expect formal-operational functions to show up somewhat sooner than in samples showing more "typical" performance. By the sixth grade (mean age: 12), one would expect formal operations to be rather firmly entrenched in children from the present sample.

2. Representation selection. The empirical evidence suggests that there was a difference from the fourth-grade level onward in the mental representations used for attributes of the two kinds of analogies. Attributes of schematic-picture analogies were represented separably; attributes of People Piece analogies were represented integrally. Moreover, the evidence suggests that there was a difference between the representations of the second graders on the one hand, and the older children and adults on the other, in solving the People Piece analogies. Second-graders appear to have separated attributes in their encodings of People Piece analogy terms, thereby allowing themselves to solve the analogies in a way that bypassed mapping. Older children and adults appear to have integrated the attributes in their encodings, and to have used this integral representation in mapping.

Individuals' introspective comments about their solution of analogies conform to the kind of difference proposed here between representations of the two kinds of attributes. Individuals solving schematic-picture analogies were very aware of individual attributes, and of testing them on a one-by-one basis. Individuals solving People Piece analogies reported choosing answers that "felt right." They were unaware of individual attributes, or even of how they arrived at the answers they chose. These differences in verbal reports suggest that the different types of attributes led not only to component and representational differences, but to strategy differences as well.

3. Strategy selection or planning. People used different strategies in solving analogies with the two kinds of attributes, except at the grade 2 level, where the identical strategy was used for analogies of both kinds. The alternative strategies that were compared differed in which components were executed exhaustively and which were executed with self-termination. Exhaustive execution of a component means that all possible attributes (in these analogies, four) are processed: Exhaustive encoding would involve encoding of all four attributes of each term; exhaustive inference would involve inference of relations between all four attributes of the first two terms; etc. (In analogies with less clearcut attributes, such as verbal ones, encoding can never be truly exhaustive, since the number of attributes that could possibly be encoded is virtually infinite; comparison of attributes can be exhaustive, however, with respect to the attributes that were encoded.) Self-terminating execution of a component means that the minimum possible number of attributes (four or fewer in these analogies) are processed: The exact number needed depends upon how many attributes must be considered before the incorrect option (or options) can be falsified, leading to selection of a unique correct response.

In the schematic-picture analogies, all components were executed in self-terminating fashion, regardless of the age of the person solving the analogy: Individuals encoded, inferred, and applied the minimum number of attributes required to obtain a solution. In the People Piece analogies, striking and systematic age differences appeared in the components that were exhaustive as opposed to self-terminating. Second graders solved the People Piece analogies in the same way that they solved the schematic-picture analogies. Fourth graders were self-terminating in all components, except the encoding component, which was exhaustive with respect to the four attributes in the problems. Sixth graders and adults were self-terminating in all components except encoding and inference.

The difference in strategies across age levels is more easily understood after working through a concrete example. Consider the People Piece analogy at the bottom of Figure 1. Figure 4 shows flow charts depicting the successive strategies that would be used by second graders, fourth graders, and sixth graders and adults in solving this analogy.

Insert Figure 4 about here

At one extreme of the age range, consider the strategy a second grader would use to solve this problem (shown in the flow chart at the left of the figure). First, the child would encode a single attribute of the first term, say, height. Next, the child would encode the corresponding attribute of the second term. Then, the child would infer the relation between the two values on this attribute (in this case, that both figures are tall). Next, the child would encode the corresponding attributes in the third term and in the answer options. Then, the child would look for an answer option that is the same height as the third term (since the second term was the same height as the first term). Since only the first term is the same height (short), it is possible to respond immediately, without checking any other attributes. Had both answer options been short, another attribute would have been checked, and attribute comparisons would have continued until an attribute was found that falsified one answer option and thereby confirmed the validity of the other.

At the other extreme of the age range, consider the strategy a sixth grader or adult would use to solve this same problem (shown in the flow chart at the right side of the figure). First, the individual would encode the first analogy term, processing all four of the attributes integrally. Next, the individual would encode the second analogy term in the same way. Then, the individual would infer the relationships between all of the corresponding attributes of these two terms, recognizing that height and weight stay the same but that sex and garment color change. Then, the person would encode the third analogy term. Next, the person would map a single relation from the first term of the analogy to the third term, say, height. Then, the individual would encode the answer options. Next, he or she would apply a single relation corresponding to the mapped one from the third term to each answer option. Since only one answer option is the correct height, the first, the problem solver is able to respond. Were it necessary to cycle through another attribute, the problem solver would map and apply successively as many attributes as would be needed to choose a unique response.

Children show a general tendency to become more nearly exhaustive in information processing with increasing age. This finding of increasing use of exhaustive information processing is consistent with findings of Vurpillot (1968) concerning visual scanning of pairs of pictures, and with the suggestion of Brown and DeLoache (1978) that increased use of exhaustive information processing is a general characteristic of cognitive development. Strategies requiring increased use of exhaustive information processing also require more information-processing capacity, because they place increased demands on working memory. In exhaustively executed components, one must remember the result of each previously performed operation. In components executed in self-terminating fashion, one need only remember that the operation was executed at all, so as not to repeat it later in solution.

Why do individuals become more nearly exhaustive in their strategies with increasing age? The reason seems to derive from the relationship between strategy and error rate. Mathematical modeling of errors reveals that not all components contribute equally to error rate: In fact, errors are due almost exclusively to self-terminating components. Presumably, incomplete information processing of the kind generated by self-terminating components is more likely to lead to a hasty and incorrect response than is complete information processing of the kind generated by exhaustive components. Thus, the sharp declines in error rates noted from grade 2 to adulthood are probably due in part to the increased use of exhaustive information processing. Older individuals choose a strategy that will minimize their error rates while still enabling them to maintain a reasonable rate of problem solving.

4. Strategy monitoring. There was no evidenee of a general shift in strategy over time. It was found, however, that in general, older individuals are more consistent in their application of any strategy at all in problem solving. Younger children seem to have trouble settling upon a strategy, and are less systematic in their information processing than are older children, who settle upon a strategy rather quickly, and then stick to it. This pattern of results extends to children observations made by Bloom and Broder (1950) in a study of the problem-solving abilities of college students: These investigators found that one of the most noticeable differences between successful and unsuccessful problem solvers was in their respective "care and system in thinking about the problem. As might be expected, the successful problem-solvers were careful and systematic in their method of attack upon the problem.... The nonsuccessful problem solvers, on the other hand, started the problem with no apparent plan for solution, more or less plunging in, not knowing what was to come next" (pp. 29-30).

5. Speed-accuracy tradeoff decision. Older children are generally less willing to trade off accuracy for speed. This difference in approach to problem solving shows itself in two ways. The first, mentioned previously, is the use by older children of a more nearly exhaustive strategy of information processing. Such a strategy increases the total number of attributes to be encoded and compared, but results in greater accuracy of performance. Second, older children tend to spend proportionately more time in encoding of stimulus terms than do younger children. This more careful encoding by older children is partially responsible for the U-shaped encoding function shown in the left panel of Figure 2. First, encoding times decrease as children become better able simply to identify attributes and store them in memory. Then, encoding times increase as children learn to spend more time in encoding. This additional time serves not only to reduce the number of errors due to sloppy encoding of the terms of the problem, but also facilitates subsequent performance of comparison operations. These subsequent operations can be performed more rapidly because the individual has a clearer picture of the stimuli being compared. An analogy can be drawn to a lending library (Sternberg, 1977b; Sternberg & Rifkin, 1979). More careful cataloging (encoding) of books results in a greater initial time investment, but later facilitates borrowing and lending of books, since the locations of the books are now known.

6. Solution monitoring. Our current knowledge about solution monitoring during analogical reasoning is extremely meager, although some interesting work on this topic has been performed by Whitely and Barnes (in press). The analogies used in the present study were quite easy, and unlikely to require extensive monitoring of the solution process. Some current work with more complex forms of analogies may serve to give us a clearer picture of how individuals monitor their solution processes.

Unifying the Three Frameworks for Understanding Intellectual Development

Three frameworks for understanding intellectual development have been presented, each of which seems to deal with somewhat different questions in a somewhat different way. All seek to explain the same basic set of phenomena, however, those characterizing intellectual development, and one would hope that ultimately the three frameworks could be incorporated into a single framework that encompasses all three. I would like to make the rather brash proposal that the componential framework may provide a basis for ultimately attaining such a unified framework.

In the psychometric framework, intellectual development is understood in terms of changes relating to the factorial composition of intelligence. But what, exactly, is a factor? This question has never been clearly answered in the psychometric framework. Defining factors as "latent traits" or as "basic abilities" seems to raise as many questions as it answers. In the componential framework, however, factors can be understood as constellations of components and metacomponents that tend to cluster together in related sets of tasks. For example, a "general" factor that embraces all of the tasks within a given task domain might well be understood in terms of two components--encoding and response--and six metacomponents--component selection, representation selection, strategy selection or planning, strategy monitoring, speed-accuracy tradeoff decision, and solution monitoring--that seem common to virtually all information-processing tasks. Individual differences in general intelligence, or "g," would then be understood in terms of individual differences in the effectiveness with which these components and metacomponents operate in a wide range of tasks. A "group" factor, such as inductive reasoning, might be understood in terms of four components--inference, mapping, application, and justification--that seem common at least to inductive reasoning tasks. The main point is that the factor, which has been defined only hazily within a psychometric framework, can be understood in quite concrete terms within a componential framework.

In the Piagetian framework, intellectual development is understood in terms of the functioning of assimilation and accommodation through four stages of intellectual development. I suspect that assimilation and accommodation are not each unitary processes, but rather sets of components and probably metacomponents that vary across tasks and task contents. The horizontal décalage that occurs within a given stage may be attributable to the fact that full attainment of the abilities required for identification with a given stage requires acquisition and efficient utilization of a number of different components and metacomponents, some of which become available at slightly later times during a given stage than others. The analogies research, for example, has suggested that identification with the formal-operational stage of intellectual development is associated with acquisition and utilization of the mapping component. But the attainment of formal operations seems to require more than just recognition of second-order relations, and the various other acquisitions that are required may each involve a different component, metacomponent, or set of each. Components and metacomponents thus complement rather than conflict with the notion of stages of intellectual development. Stages will appear if the acquisition and utilization of certain components and metacomponents tend to go together developmentally, perhaps because they tend to be used together in real-world tasks. In other words, a given class of tasks (such as conservation problems or transitive inference problems) will be soluble by a child or adult only if the individual possesses all of the components and metacomponents required to process the problem from the beginning to the end.

The above suggestions provide only the barest sketch of what a unified framework for understanding intellectual development might look like. I believe that with time, however, it will be possible to fill in some of the details of this sketch. A unified framework for understanding the development of human intelligence within the context of a unified theory of human intelligence seems like a desirable, if distant, goal.

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Footnotes

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[1] This point was suggested by Janet Powell.

[2] Analogical reasoning has been investigated intensively, in large part because of its traditional centrality in theories of intelligence (see Spearman, 1923; Sternberg, 1977b). To this day, analogies are found on a large number of psychometric tests of intelligence. Indeed, one widely used test, the Miller Analogies Test, is composed exclusively of analogies. A number of other reasoning tasks have been investigated as well, however (see Sternberg, in press-e, for a summary of findings for these various tasks).

[3] This section represents a distillation of discussion found in Sternberg (1979). An elementary consideration of these issues is found in Sternberg (in press-b).

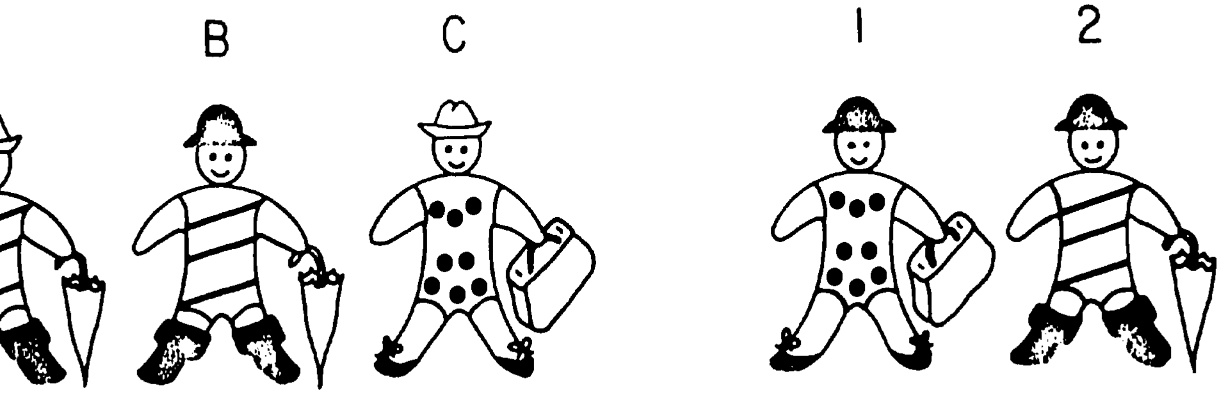
[4] Although illustrative examples will be drawn from a single set of experiments on the development of analogical reasoning (Sternberg & Rifkin, 1979) in order to maintain simplicity and to provide continuity, other studies of the development of analogical and other forms of reasoning have been done as well that make use of componential methodology (Sternberg, in press-a; Sternberg, Note 3; Sternberg & Nigro, Note 4).

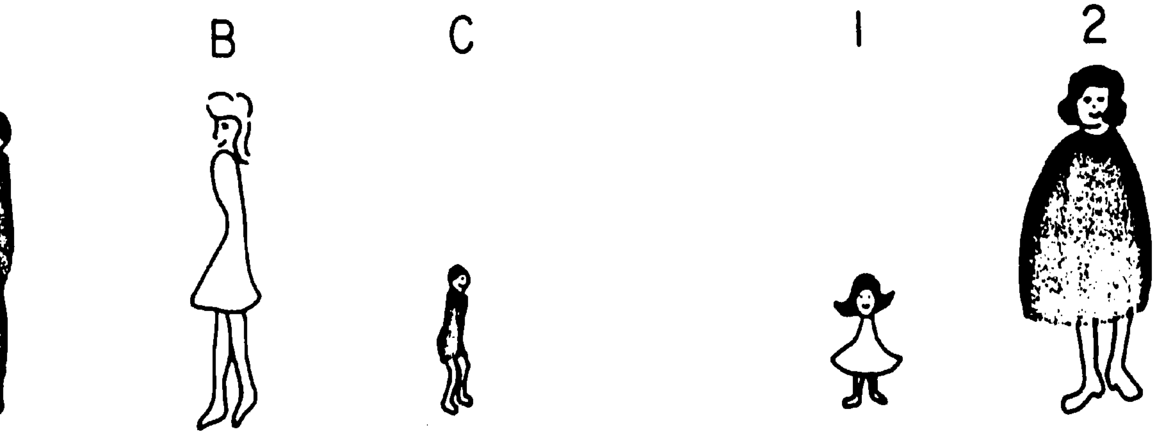
Figure Captions

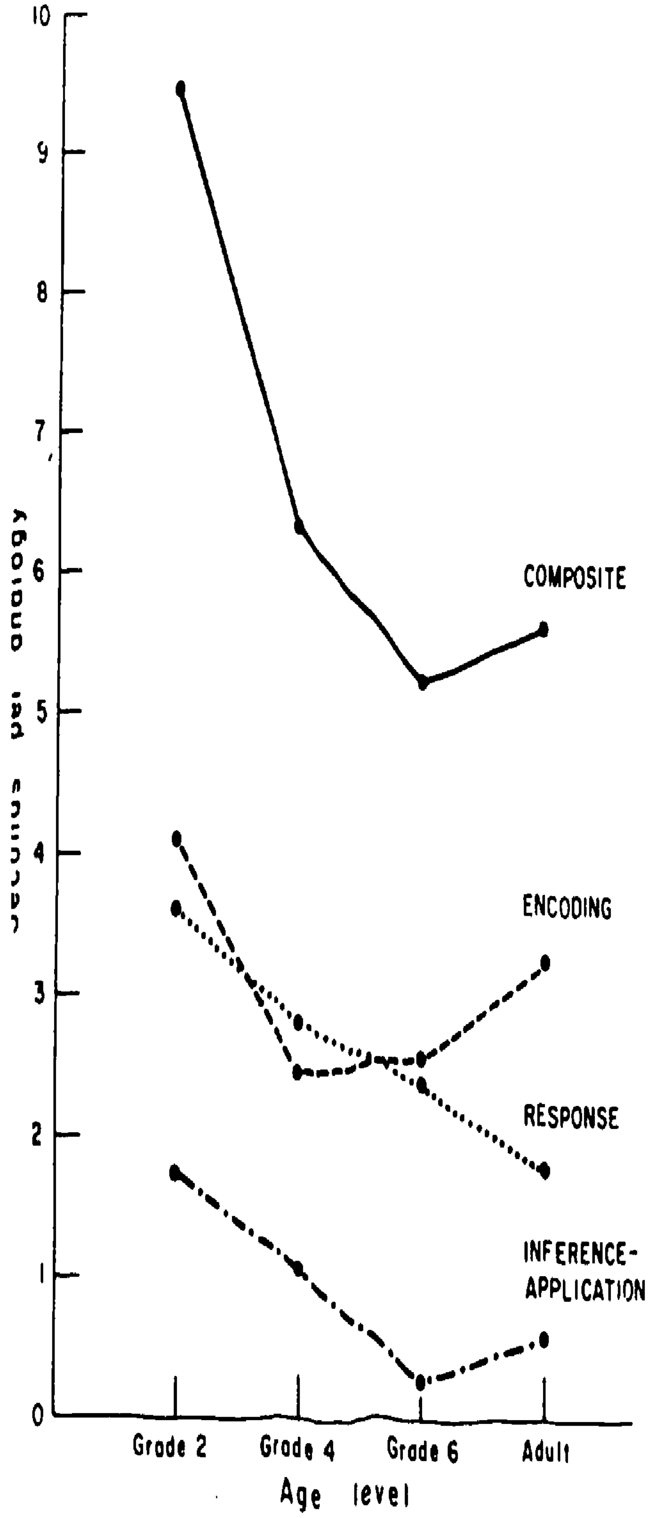
1. An example of a schematic-picture analogy (top panel) and of a People Piece analogy (bottom panel).

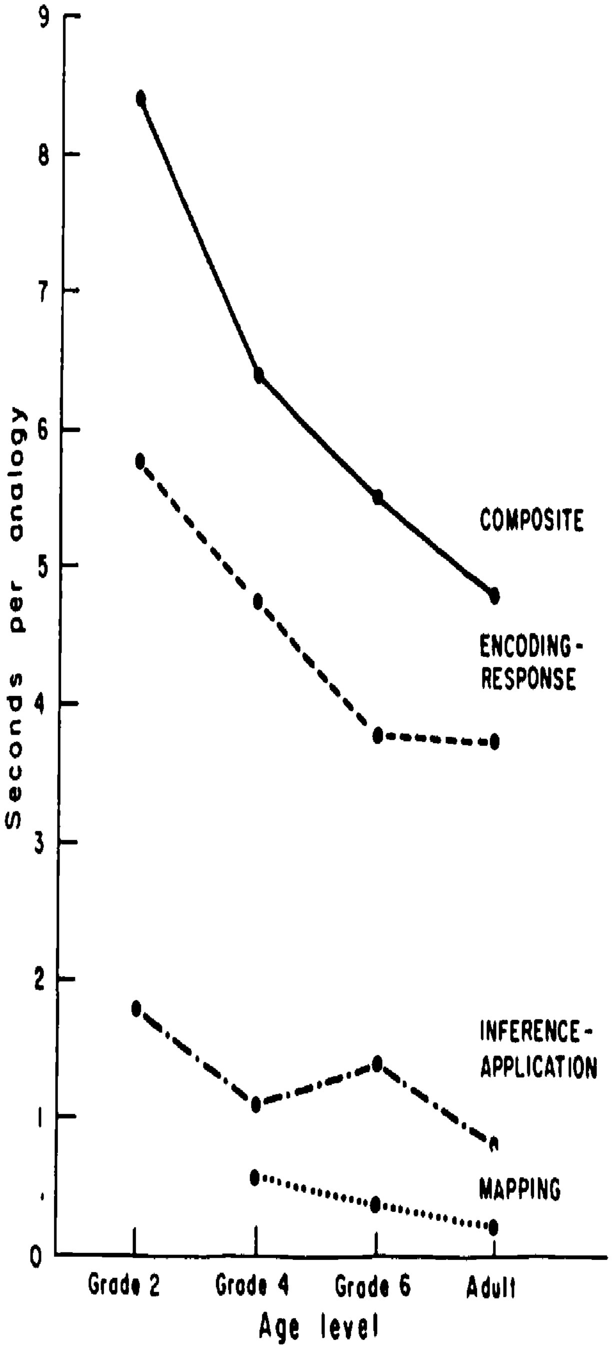
2. Composite and component latencies of correct responses to schematic-picture analogies (left panel) and to People Piece analogies (right panel).

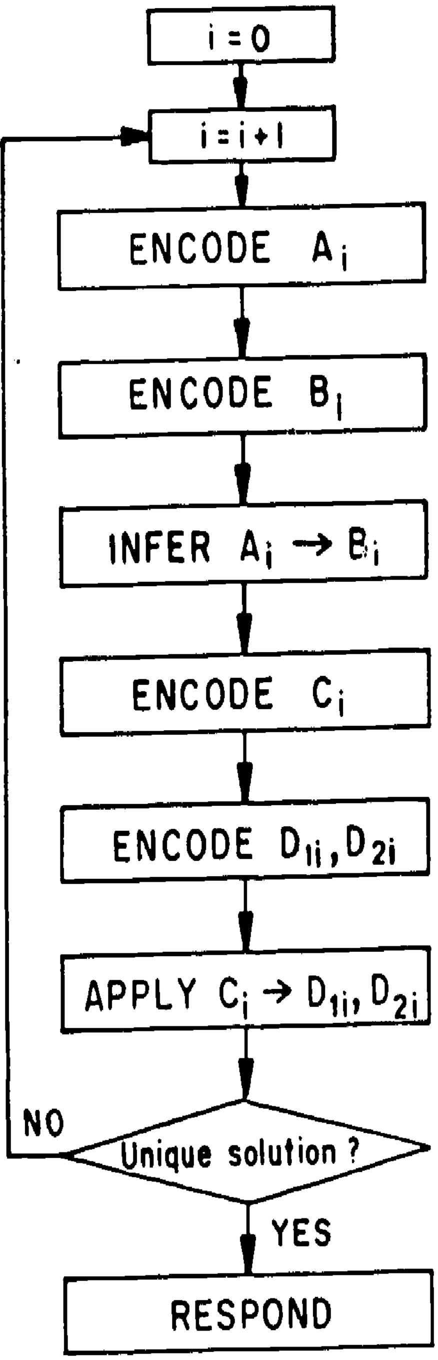
3. Flow charts depicting strategies used in the solution of analogies of the form A : B :: C : (D_1, D_2). The left panel shows the strategy used by individuals of all age levels in solving schematic-picture analogies with separable attributes, and by second-graders in solving People Piece analogies with integral attributes; the middle panel shows the strategy used by fourth-graders in solving People Piece analogies; the right panel shows the strategy used by sixth-graders and adults in solving People Piece analogies. The subscript i refers to an attribute of an analogy term.

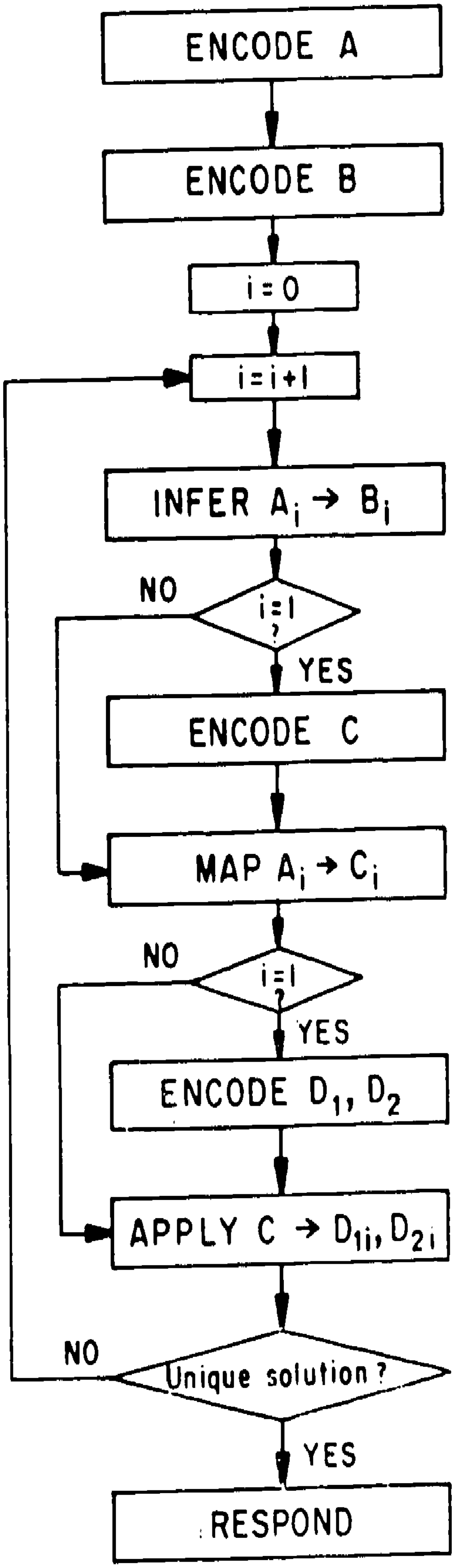

B
C
1
2

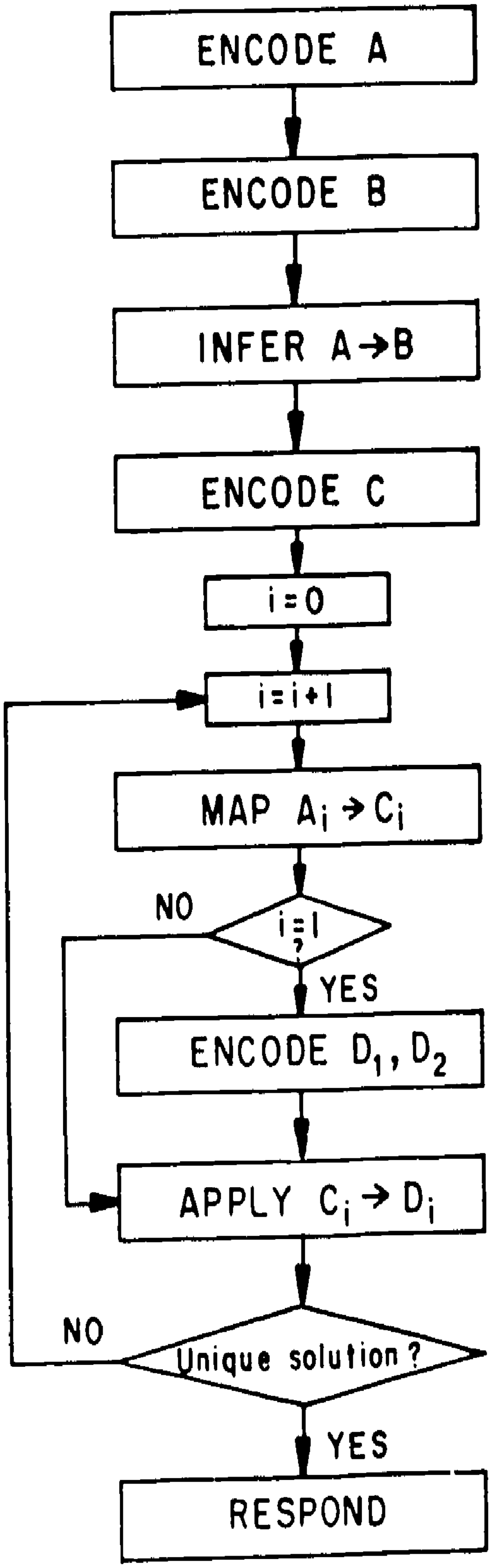

B
C
1
2


Seconds per analogy
10
9
8
7
6
5
4
3
2
1
0
COMPOSITE
ENCODING
RESPONSE
INFERENCE-APPLICATION
Grade 2
Grade 4
Grade 6
Adult
Age level


Seconds per analogy
9
8
7
6
5
4
3
2
1
0
COMPOSITE
ENCODING-RESPONSE
INFERENCE-APPLICATION
MAPPING
Grade 2
Grade 4
Grade 6
Adult
Age level


i = 0
i = i + 1
ENCODE A_i
ENCODE B_i
INFER $A_i \rightarrow B_i$
ENCODE C_i
ENCODE D_{1i}, D_{2i}
APPLY $C_i \rightarrow D_{1i}, D_{2i}$
Unique solution ?
NO
YES
RESPOND


ENCODE A
ENCODE B
i = 0
i = i + 1
INFER $A_i \rightarrow B_i$
i = 1 ?
NO
YES
ENCODE C
MAP $A_i \rightarrow C_i$
i = 1 ?
NO
YES
ENCODE D_1, D_2
APPLY $C \rightarrow D_{1i}, D_{2i}$
Unique solution ?
NO
YES
RESPOND


ENCODE A
ENCODE B
INFER $A \rightarrow B$
ENCODE C
i = 0
i = i + 1
MAP $A_i \rightarrow C_i$
i = 1 ?
NO
YES
ENCODE D_1, D_2
APPLY $C_i \rightarrow D_i$
Unique solution ?
NO
YES
RESPOND

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