CONTENT KNOWLEDGE: ITS ROLE, REPRESENTATION, AND RESTRUCTURING IN MEMORY DEVELOPMENT

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I. Introduction

Changes in a person's acquired knowledge have long been recognized as a distinguishing feature of cognitive development in general, and memory development in particular. However, although many people, including of course Piaget (Piaget & Inhelder, 1973), have alluded to the importance of "memory in the wider sense" as extremely relevant in cognitive development, only since the mid-1970s have researchers directly examined the role of knowledge in memory development. In Sections II and III of this article we discuss our interpretation of the forces that are responsible for this shift in emphasis. Next, we selectively review specific studies that demonstrate the causative role of knowledge in producing age-related differences in memory (Section IV). Finally, drawing upon empirical studies (Section V) and theoretical analyses (Section VI), we examine how the knowledge structure changes with development. In all of this discussion we tend to emphasize (perhaps overemphasize) the role of one type of knowledge as it relates to the development of memory, namely *content* knowledge. This near-exclusive emphasis on content knowledge is a result of its demonstrable influence on children's memory performance—an influence that was neglected by researchers for many years. We conclude with a few qualifying statements about what aspects of knowledge have been omitted.

II. Why Knowledge Differences Were Not Considered in the Past

Although knowledge in a general sense (as referring to the contents of long-term memory) has always been considered an important aspect of development, the dominant developmental focus, particularly from the Piagetian perspective, has been on the availability of certain logical structures. These logical structures were presumed to be applicable across many domains of knowledge. Consequently, little attention was paid to the role of the content of knowledge, that is, what the child knows and how it might influence the use of logical structures. Later, however, theorists began to express dissatisfaction with such universal models of general cognitive growth, providing provocative arguments for contextual constraints (including the presence of local knowledge) on the child's deployment of logical structures (Ceci & Bronfenbrenner, 1985; Gardner, 1983). Today, ample evidence points to the importance of content knowledge, not as an adjunct to cognition, but as a constituent of it (Chi, 1978, 1985). Thus, the formerly popular approach to studying cognitive structures and operations disembodied from a child's knowledge about the problem at hand is being challenged by research that demonstrates the importance of knowledge in both perceiving the problem at hand and shaping one's solution of it (Lave, Murtaugh, & de La Roche, 1984). In this section, we discuss what misconceptions about the role of content knowledge historically could have produced a lack of concern to consider it an important source of cognitive development.

A. MISCONCEPTIONS ABOUT THE ROLE OF KNOWLEDGE

One reason for the lack of focus on content knowledge, we believe, is that many researchers may have implicitly assumed that its contribution to the cognitive task at hand was negligible. Take the simplest memory task, digit span, as an example. The usual assumption has been that having the capability to identify the digits is a sufficient criterion for performing maximally on the digit-span task. Hence, any developmental differences obtained with span measures must be attributed to other prominent factors such as processing efficiency, strategic differences, or capacity differences (e.g., Case, Kurland, & Goldberg, 1982; Chi, 1976; Huttenlocher & Burke, 1976). However, one could argue that measuring a child's ability to identify or name a digit does not constitute a sensitive measure of digit knowledge, or how easily or competently one can manipulate digits. A more sensitive measure might be how quickly a child can name a digit.

We do know, for example, that children take longer to name a digit or identify a face than an adult, even after motor (vocalization) time is partialed out (Chi, 1977; Morin & Forin, 1965). In fact, children are known to be slower than adults at processing information on both very simple tasks such as responding to the onset of a tone (Surwillow, 1977) and more complex tasks such as encoding chess patterns (Roth, 1983).

What is the implication of such slower encoding time on digit span? If we assume that children's active memory decays at the same rate as adults' (Chi, 1976), then the fact that children take significantly longer to encode (or name) a digit would seem to imply that the early items of a list that were encoded would have decayed while the child is still processing and encoding the subsequent digits in the list. For instance, using a visual presentation of an array of familiar faces, 5 year olds on the average took 1531 msec to name a face, whereas adults took only 666 msec. Likewise, children required an exposure duration of 138 msec to recognize one face whereas adults needed only 26 msec (Chi, 1977). Although this research used a visual presentation to measure encoding, similar developmental differences must also be assumed for auditory presentation, given that we already know that it takes children longer than adults to respond to the onset of a tone (Chi & Gallagher, 1982). Extrapolating from such results, one could say that the speed of encoding digits can potentially limit children's recall span. In fact, evidence now exists to support this claim directly. Nicolson (1981) found a linear relation between memory span and reading rate for different types of materials, independent of age (in the age range of 8–12 years). That is, the faster a child can read a digit, the longer is the span. Case *et al.* (1982) extended this result downward to the 3–6 age range and, moreover, showed that when adults are forced to reduce their speed of processing (by using an unfamiliar number list to count), their span also decreases. Hence, the speed with which one encodes the stimuli clearly limits the amount that one can recall in a span task.

The existence of a trade-off between speed and span clearly suggests that we cannot assume that children and adults have sufficient knowledge of digits to perform optimally on a span task. We have to understand the sources of a slower speed of encoding. From a knowledge perspective, one could attribute slower encoding speed (after partialing out vocalization speed) to the way the stimulus is represented in memory. For instance, greater knowledge of a digit might imply that it has a greater number of (or stronger) pathways leading to it, thus allowing for more rapid access and search, resulting in faster naming. This interpretation, that the representation of some digits may be different from others, is consistent with what we have known for some time, namely, that for adults, certain numbers are more salient than others. Wertheimer (1950), for example, suggested that certain numbers take on the roles of reference points for the entire number system. Thus, adults consider that "103 is virtually 100" is reasonable but "100 is virtually 103" is not (Rosch, 1975). We do not know, however, whether children use similar numbers for these reference points, or whether they even use such reference points.

One can, furthermore, demonstrate the existence of individual and developmental differences in number knowledge quite directly. Using similarity judgments of digit pairs as their basis, Corsale and Gitomer (1979) discovered that students who were poor solvers of arithmetic analogy problems of the kind "3 : 6 : : 4 : X" had fewer dimensions with which to represent digits. The dimensions they possessed were (1) shape of a number and (2) odd vs. evenness. More successful solvers of the same age often had additional dimensions by which to represent digits, such as whether or not each is a prime number, whether two numbers are related multiplicatively or exponentially, etc. Miller and Gelman (1983) also found that the older children, like the more successful solvers in the Corsale and Gitomer study, can represent digits along a greater number of dimensions, and thus may have a more elaborated network with which to encode them, thereby allowing for faster and easier access. Thus, the speed of numerical access can be interpreted in terms of the way digit knowledge is represented.

The foregoing discussion thus questions the common assumption that, beyond number facts, digit knowledge is developmentally invariant, and raises the possibility that differential knowledge may substantially affect performance on a very simple task such as digit span. We believe that content knowledge plays even a larger role in the performance of more complex tasks such as the balance-scale task that Piaget introduced and Siegler subsequently analyzed. According to Siegler (1976), young children are unable to solve this task because they do not encode the relevant dimensions. We would interpret this to mean that younger children have fewer dimensions with which to encode weights. Essentially, younger children do not know what dimensions are important and relevant for encoding the weights—such as the distance from the fulcrum or the heaviness of the weights. Thus, a reasonable assumption is that the facility with which a child can encode and represent the stimulus materials (such as digits or the balance scale weights) will effect performance on tasks involving these stimuli.

B. CHILDREN HAVE ADEQUATE KNOWLEDGE BUT LACK SKILL

A second misconception about the role of content knowledge may have been the assumption that children do have adequate knowledge to handle the task presented. Their failure to perform as well as older children is attributed to the lack of a specific skill. (This assumption is slightly different from the one presented in Section II,A, which stated that the knowledge needed for the task is trivial.) A good measure to illustrate the common misconception that children do have adequate knowledge but lack the skill is the amount of clustering in free recall. The usual finding is that younger children do not cluster items into taxonomic categories as readily as do older children. The adult data show, in general, that when items belonging to different categories (such as animal, clothing, furniture, vehicles) are randomly presented to them, their recall sequences manifest clustering of items that belong to the same taxonomic category (Mandler, 1967; Tulving, 1962). Young children, in contrast, are not as likely to show taxonomic clustering (Ceci & Howe, 1978a; Cole, Frankel, & Sharp, 1971a; Laurence, 1966; Nelson, 1969; Shapiro & Moely, 1971).

Young children's deficit in category clustering during free recall can be manifested in related tasks as well, such as sorting. That is, young children often do not group together items from the same superordinate category. Instead, they tend to group items for a variety of other reasons, such as perceptual similarity (Melkman, Tversky, & Baratz, 1981; Tomikawa & Dodd, 1981), concrete situations (Goldman & Levine, 1963; Olver & Hornsby, 1966), associations, and narrative themes (Ceci & Howe, 1978a). Such results have usually been taken to mean that the younger children lack an understanding of hierarchical classification, a skill which develops, presumably, with age.

Although failure to categorize the stimuli on a superordinate basis in a sorting task may or may not be explained by the same source of difficulty as the lack of clustering in free recall (Chi, 1985), both measures have been partially attributed to the same general deficiency, namely that children do not possess abstract classification skills, rather than the possibility that children may simply not possess knowledge of taxonomic categories. Yet, despite its alluring intuitiveness, this latter interpretation has been rejected by some researchers for several reasons. They argue that children basically do have adequate knowledge; that is, it has been assumed that categorical (taxonomic) knowledge is available even to the youngest children for the stimulus materials tested. This conclusion is based on a variety of techniques used to assess categorical knowledge. In the majority of the cases, assessment of categorical knowledge relies on the use of supplementary or secondary tasks in conjunction with the primary task of sorting or free recall. Liberty and Ornstein (1973), in a postexperimental task, asked 9 year olds to group "things that go together." The children's ability to do this task successfully was taken as evidence that they possessed knowledge of the semantic relations among the items. Therefore, older children's taxonomic sorting is attributed to the fact that they use this knowledge to organize their recall and younger children's lack of taxonomic sorting is viewed as a "production deficiency."

In a similar vein, Kobasigawa and Middleton (1972) also established that young children had explicit knowledge of taxonomic categories by asking them during the posttest interview to identify the 6 picutres (out of 24) that belonged to each of the 4 taxonomic categories. None of the children (even the 5 year olds) had any difficulty doing this secondary task, even though their taxonomic clustering and recall scores were significantly worse than the fifth graders'. Again, this finding was taken as evidence for the availability of taxonomic knowledge that was *not* used by young children for the purpose of sorting or clustering. We present an alternative interpretation, based on the notion that these assessments of the availability of knowledge may not capture the nature of the representation or organization of that knowledge, therefore one cannot safely conclude that children do have sufficient (categorical) knowledge to perform the task. This interpretation is discussed at the end of Section II,C, because it can serve as an alternative explanation for both the assumption presented in this and the next section.

C. CHILDREN PREFER NOT TO USE THEIR KNOWLEDGE

A third reason for not focusing on the role of content knowledge is the assumption that children prefer not to use their knowledge. For example, Smiley and Brown (1979) asked children whether two taxonomically related items could be paired (the secondary task), even though the children did not initially choose them to be related in a triad preference test (the primary task). Their ability to give correct justifications for the taxonomic pairings was taken to mean that younger children simply *prefer* to use functional and perceptual relations, not that they do not have the capacity to do so. In addition, 5-year-old children could be trained to match on the basis of taxonomic relations, providing further support for the notion that children can encode taxonomic relations. Finally, Ghatala and Levin (1982) showed that drawing children's attention to taxonomic organization facilitated their recall, thus supporting the view that young children's cognitive shortcomings are not due to a lack of knowledge.

Although Smiley and Brown (1979) proposed an alternative interpretation for young children's classification failures (they simply prefer to use nontaxonomic relations when sorting items) to the commonly accepted one mentioned in Section II,B (i.e., that they have a deficit in classification skills), both views require the assumption that the content knowledge needed for the classification is basically there and that the existence of this knowledge can be shown in one of the many ways just described. We question, however, the validity of the premise that the content knowledge exists and, moreover, that it exists in a form that is readily usable. Basically, we propose that successful performance on these secondary tasks requires only that one or two salient dimensions of a category be used. For example, in the Kobasigawa and Middleton task, children can successfully pick out six pictures that belong to the animal category simply by knowing only whether each item pictured is or is not an animal. This requires only the knowledge that a dog (if it is depicted) is an animal. We have argued elsewhere (Chi, 1983a, 1985) that the ability to confirm correctly that a dog is an animal only requires that the child has the knowledge that "animalness" is an attribute of dogs. That is, for a young child, "animal" may be just another attribute of "dog" just as, say, "bark," and not necessarily the name of a superordinate category linking specific animals to a unified structure. Thus, knowing that a dog is an animal need not imply that the child possesses the entire hierarchical structure with animals on the top-level node, and different categories of animals on the lower-level nodes, as one might expect in a perfect canonical adult representation (Rosch, Mervis, Gray, Johnson, & Boyes-Braem, 1976). Nor does a young child's ability to perform such a task imply that the young child's representation of animals is as rich as the older child's. In fact, we see in Section V,A that in studies aimed at depicting children's representation of knowledge (as in multidimensional scaling of animal terms), adults generally have more consistent and abstract dimensions, whereas younger children have fewer dimensions with which to represent animals. Furthermore, the younger children's dimensions are more thematic, perceptual, and inconsistent, and less "taxonomic" (Ceci, Lea, & Howe, 1980). Hence, one interpretation of the successes on secondary task performance is that it taps only one or two dimensions or attributes of concepts that are especially salient, even to the youngest children. To perform successfully on the primary task, however, requires the additional knowledge of either the hierarchical structure of the whole set of concepts or the interrelations among them. When confronted with tasks that require such extensive semantic knowledge for their successful completion, clear-cut developmental differences are to be expected.

To summarize, we have briefly discussed three kinds of cognitive tasks (memory span, Piagetian-type tasks, and sorting tasks) illustrating three kinds of interpretations of children's deficient performance, namely that (1) the contribution of knowledge to the task is negligible, (2) children have the knowledge but lack the skill, and (3) children have the knowledge but prefer not to use it. We have presented an alternative interpretation, suggesting that the contribution of knowledge is not negligible, and further that in order to assess the adequacy of children's available knowledge, one must try to capture an entire (integrated and coherent) knowledge structure. Secondary tasks that are used to assess the existence of knowledge can often be performed with more isolated and piecemeal knowledge, but performance on the primary tasks requires a more integrated and cohesive knowledge structure.

We further envision two fundamental problems with the second (skill deficit) and third (preference) interpretations. They tend to imply that the knowledge needed is there or not in an all-or-none way. Our explanation (presented throughout this article) centers not so much on such a presence/absence dichotomy, but rather on how that knowledge is represented.

A second problem with the skill-deficit interpretation is the implication that a fundamental reorganization of knowledge must necessarily occur in order for a child to be able to handle or process information in a particular way. This view requires the assumption that a skill, such as classification, cannot occur until the emergence of certain structures. The results from the secondary tasks ostensibly support this notion. These results suggest that the relevant knowledge is present, but somehow cannot be or is not used (the implicit assumption being that the requisite skill is not there to use). Our interpretation of the results, as stated earlier, is that the way knowledge is assessed on these secondary tasks does not justify assuming that it exists in the same form for young children as for older children or adults. Hence, we question the premise of the interpretation (that the knowledge is present), not so much the conclusions (that children lack the skill to classify or that children prefer not to classify in a certain way). We believe that having the relevant knowledge represented in the appropriate form is inextricably related to the manifestation of a skill.

D. CHILDREN CANNOT ACCESS THEIR KNOWLEDGE

Finally, a popular fourth interpretation of children's performance deficits is that children cannot access the knowledge they have (Brown, 1982; Rozin, 1976). If we interpret *access* literally (i.e., an inability to get at existing knowledge), this explanation also focuses less attention on the role of knowledge per se, but instead concentrates on the inadequacy of an accessing mechanism. However, because the literature has been unclear about what constitutes an adequate or inadequate accessing mechanism, one could reinterpret the accessing view to be compatible with a knowledge-representation view. That is, one could say that an accessing failure implies a knowledge organization which is incoherently represented (as can be shown by scaling solutions, for example), not well integrated, not hierarchically organized in a way that is optimal for utilization on such tasks. Thus, to say that young children cannot access their knowledge could be interpreted to mean that a child's knowledge is not represented in such a way as to make it accessible. Viewed this way, an access interpretation becomes one that is concerned with knowledge representation and reorganization. We will briefly sketch topics of research which point to the role of knowledge as an important source for explaining performance differences.

In summary, our thesis in this section is not only that children and adults cannot be assumed to have equivalent knowledge about a task and the stimuli, but also that the tasks that have been used to tap the availability of knowledge have limitations. None of the tasks has been successful in uncovering the exact representation of knowledge, and therefore we cannot explain adequately why children appear to be unable to use their knowledge, assuming they even possess it in the first place. Our hypothesis, to be elaborated in Section V, is that younger children's knowledge is really not represented in the same way as older children's and adults' (unless young children have expertise in a particular knowledge domain). Consequently, younger children cannot use their knowledge in the same way as older children. Two empirical methods can be used to confirm this hypothesis. The simpler method is to show that children's knowledge is represented differently from adults' (as alluded to earlier in this section, and developed more fully later). The more difficult way is to show that when young children do have equivalent knowledge to older children or adults (as measured by some external criteria), their representations tend to be similar. That is, the existence of an apparent equivalent amount of knowledge in two groups of subjects as measured by some external quantitative index cannot be taken to indicate that a similar internal coherence exists in the representations, unless additional (usually more sensitive) measures are taken to uncover the structure of knowledge. Research on chess knowledge, however, did show that children who are experts in the game of chess (as indicated by an external index) also represent chess knowledge in the form of chunk structures much like those of the adult chess experts (Chi, 1978).

Developmental differences in knowledge traditionally have not been assessed for several additional reasons that we have ignored. The most obvious one is that invoking a strategic deficiency provides a much simpler explanation of children's inadequate performance, given the conclusive evidence that (1) younger children are deficient in the use of adult strategies; (2) development of strategies do correlate with better performance in both children and adults; (3) when children are trained to use strategies, their performance improves; and (4) when adults are prevented from using strategies, their performance deteriorates. We need not elaborate here the evidence for the general assumption that the acquisition and use of strategies can explain developmental data to a large extent, not because it is of lesser importance, but mainly because such evidence can be found in many summary chapters (see for example, Kail & Hagen, 1977). However, one must keep in mind that the increasing and improved use of strategies is just one factor that explains developmental performance trend; furthermore, one needs to explain the underlying mechanism that accounts for the improved and increased use of strategies with age. In the next section, we focus instead on several factors emerging in the 1970s that we believe have contributed to a general orientation toward the role of content knowledge in development.

III. General and Specific Factors That Contribute to a Focus on Content Knowledge

Despite the earlier assumption that knowledge is equivalent between children and adults (or at least adequate for both groups' task performance), several factors emerged in the 1970s to implicate knowledge as an important source of developmental differences. We briefly sketch five topics of research which point to the role of knowledge as an important source for explaining performance differences.

A. DISILLUSIONMENT WTH THE STRATEGY EXPLANATION

One specific factor that has led researchers to consider knowledge-base differences as causes of young children's poor memories is a dismay with the adequacy of *strategic deficiency* as a general explanation of developmental differences in memory. The reason for the dismay is that age differences often remain even when one manages to minimize strategic differences (Chi, 1977). One can attempt to reduce strategic differences in several ways. One way is to use tasks that do not require conscious strategic processing. Brown and Scott (1971), for example, used a recognition paradigm in which minimal use of retrieval strategies was needed. And indeed, preschool children were able to recognize old from new pictures as efficiently as adults could, supporting the traditional conclusion that strategies play a significant role in developmental differences in free recall. However, later studies have revealed that if the "old" and "new" pictures were very similar, then adults do tend to be more accurate than young children at recognizing the old pictures (Sophian & Stigler, 1981). Therefore, it is not clear what factor produced such age differences in performance.

A second way to reduce the role of strategies is to examine memory differences in age ranges in which no strategy differences should exist (e.g., in the age range of 2–4 years). Myers and Perlmutter (1978) assumed that very young children, in the 2–4 age range, do not adopt strategies that are typically used for memory tasks, but found that recall improved with age. Thus, this suggests that some factor other than differences in strategic processing must have accounted for the developmental differences in recall.

A third way to reduce strategic differences is to teach the younger children to use strategies as competently as older children or adults, or somehow to facilitate the use of strategies. One example of the latter approach was used by Huttenlocher and Burke (1976) when they explicitly provided children of different ages with a grouping strategy in a digit-span task. That is, the array of digits was temporally grouped to facilitate encoding, on the assumption that older children normally would group them and younger children would not. As it turned out, both younger and older children benefited from the grouping, yet age differences remained. Similar results were obtained by Samuel (1978) and by Lyon (1977) for adults with different memory spans. That is, the experimenter-imposed organization provided no differential benefit for either younger and older children or for adults with varying spans.

At the time of these studies, the implication was that grouping per se, although useful in elevating performance to some extent, has quite limited effects. We now have a better understanding of the limiting effect of grouping. It is clear that unless one can recognize a grouped unit as a meaningful pattern, grouping per se cannot enhance processing in a significant way. The most extreme example is the Chase and Ericsson (1981) study of a long-distance runner. Although the subject had developed strategies to group 80-digit strings into groups of three and four numbers, each group would have been meaningless except that the runner could recode each group into a meaningful running time. Hence, the importance of the role of one's knowledge base in remembering was demonstrated in the late 1970s, but the actual evidence of the interaction between the use of a strategy (such as grouping) and the knowledge base (meaningful digit sequences to recode the groups) was not available until the 1980s, although several verbal learning studies had made the same point a decade earlier. For example, although recalling a sequence of letters (FBIJFKTV) is well known to be facilitating if the sequence is regrouped as FBI JFK TV (Bower, 1970), the developmental community had not been convinced that children's reduced ability to benefit from such grouping is implicated as much by the lack of content knowledge (not knowing about FBI) as a reluctance to use a grouping strategy.

Besides facilitating the use of strategies (e.g., by presenting the stimuli in groups), one could of course directly teach children how to use a particular strategy in order to maximize its use. Traditional training studies typically have demonstrated enhancement of children's task performance. But the lack of transfer and generalizability has long been recognized, and the source of such limitation has not been dealt with adequately. One could reasonably postulate that strategy training requires the elaboration of the condition part of the strategic rule (much like the condition part of a production rule), which in turn requires the development of corresponding knowledge in the knowledge base. Hence, in brief, our analysis of the failure of training studies implicates a failure to teach the corresponding content knowledge necessary to use the rule (see Chi, 1983b, for an extended discussion).

A fifth method to reduce strategic differences is to prevent the older children or adults from using strategies that are available to them but not to the younger children. For example, using stimuli that were equally familiar to adults and children [faces of classmates], Chi (1977) systematically reduced the adults' opportunity to use strategies in a serial recall task by manipulations such as limited exposure and enforced sequential retrieval. She found that adults' performance on such a task did not deteriorate that much if a single strategy was deleted from their repertoire of strategies. Only when the adults were prevented from using a number of strategies available to them did their performances decrease to the level of the 5-year-old children's performance.

In sum, we have cited five research approaches to reduce strategic differences between age groups: (1) using tasks that do not require conscious strategies, (2) testing age ranges which presumably show no differences in strategy use, (3) facilitating the young children's use of strategies, (4) directly training the use of strategies, and (5) preventing adults from using strategies. The results of these studies suggest that although strategic improvement is a prominent factor in accounting for developmental differences in memory, age differences often still remain, except in the rare case where stimuli familiarity between age groups is controlled (Chi, 1977). The remaining age differences may be explained by subtle differences in the content knowledge.

B. CROSS-CULTURAL, SOCIAL CLASS, AND INDIVIDUAL DIFFERENCES RESEARCH

Cross-cultural research, due to its examination of variables such as schooling and urban living, necessarily implicates the role of experience (and its accompanying knowledge) as a source of cognitive development. The results consistently show that schooled and urban children and adults generally perform at a more sophisticated level than unschooled and rural children on tests of recall and reasoning. For example, the schooled and urban children are much more likely to answer abstract questions involving logical reasoning and more likely to show clustering in free recall than unschooled children and adults (e.g., Cole, Gay, Glick, & Sharp, 1971b; Scribner, 1977; Wagner, 1978). The data are not entirely clear, however, as to just what kind of knowledge is gained from urban and school settings that enhances these abilities. Schooling and urban living can certainly produce a broader general knowledge base, which can, according to our view, directly induce the manifestation of skills such as clustering. That is, as was alluded to in Section II,C of this article and more extensively in Chi (1983a, 1985), clustering in a specific knowledge domain can be obtained from young children's recall pattern if the information in that knowledge domain is organized in a certain way. However, it is still not clear in such circumstances whether the manifestation of clustering in recall is due to the application of a retrieval skill or whether the organization of knowledge is automatically revealed during recall by the nature of the way related knowledge is associated in memory (and thus retrieved in a particular order). Lange (1978) has made a similar point. We cite three additional examples below to illustrate the relationship between the availability of knowledge and the use of clustering and sorting skills. In addition, the knowledge base may provide the necessary background for logical reasoning in specific domains and may facilitate the acquisition of logical skills in general. Although this last interpretation of the importance of knowledge is indirect, it nevertheless points to knowledge as a key general source of achievement in terms of recall, recognition, and use of processing strategies in the cross-cultural studies (Wagner, 1978).

A fascinating study by two cognitive anthropologists sheds some light on the mechanisms by which the knowledge base mediates memory and the deployment of classification skills, including class inclusion (Lancy & Strathern, 1981). Two groups of Papua New Guinean children were studied: Ponam and Melpa. The Ponam Islanders are a fishing people inhabiting a tiny sand cay just off the coast of Manus Island (popularized in some of Margaret Mead's studies of Oceania).

They exchange fishing products for agricultural products with neighboring farmers. The Melpa are horticulturists and pig keepers who reside in the hills.

The researchers administered sorting, class-inclusion, and free-recall tasks to children of varying ages, using stimuli from categories common across both the Ponam and Melpa cultures: foods, decorations, tools, and people. Ponam Island children, who resembled Western children in the development of taxonomizing, clustering, and free recall, dramatically outperformed the Melpa children on all measures. Ponam children's performance on these and other cognitive tasks showed increases only with increases in schooling. Age itself did not account for variation in their performance.

Faced with the disconcerting possibility that Melpa children could not recognize the taxonomic structure of familiar materials (nor use it to sort or cluster), the researchers repeated the experiment using different stimuli for Melpa and Ponam children, items that were selected from "tighter" categories (higher within-culture consensus). Melpa children were discovered to behave similarly to the Ponam children on most measures when these stimuli were used. Their lone "deficit" was their class-inclusion performance. In a third experiment, some of the Melpa materials, found to be inappropriate for various reasons, were changed. With this final revision, Melpa children behaved like Ponam (and Western) children in all important respects. In the context of the present article, Lancy and Strathern's (1981) study is important for its demonstration of the effects of the knowledge base on cognition. Melpa children appeared unable to solve a class-inclusion problem, to cluster, or to recall familiar items adequately until materials were found that were highly salient, that is, materials that correspond to the structures of knowledge that they do have.

Similar results have been found in research on social class differences within a given culture. Regarding the use of classification skills, for example, it has been shown that children with lower socioeconomic backgrounds sort items on the basis of thematic relations, whereas middle-class children sort on the more abstract basis of categorical groupings, which is an indication of a hierarchical knowledge structure (Sigel & McBane, 1967; Sigel & Olmstead, 1970). However, Simmons (1985) has recently shown that such social class differences in categorical responses can be removed or even reversed if the stimulus materials used are culturally salient to them.

Ceci and Liker (1986) have demonstrated that adults who otherwise appear to be operating at low levels of intellectual functioning (e.g., IQs in the 80s) were capable of complex classification and reasoning processes when the stimuli were very familiar to them. In this study, men with low IQ were able to engage in what amounted to a form of multiple-regression-type thinking when they attempted to select winners at a racetrack. Interestingly, while these men's level of formal schooling predicted their IQs very strongly ($rs \geq .90$), neither schooling nor IQ correlated with the complexity of their thinking when the materials were highly familiar ($rs \leq .07$). It was suggested that schooling imparts a great deal of factual knowledge that is directly and indirectly tapped by IQ tests. Thus, when the usual correlation between content knowledge and schooling is violated, as when knowledge of racing facts is assessed, content knowledge (not schooling or IQ) predicts the complexity of reasoning (see Cole *et al.*'s seminal study (1971b) of the distinction between "cultural" and "school" knowledge as it relates to memory and cognitive processes). Hence, cross-cultural research, social-class research, and research on individuals of differing intellectual abilities all demonstrate the importance of both general knowledge and specific content knowledge to maximize performance for a given group of people. [Also see Rogoff, Gauvin, & Ellis (1984) for a complete review.]

C. CONSTRUCTIVE MEMORY

A third line of research, studies on constructive memory, also implicates knowledge as a source of developmental differences. The concept of constructive memory is simply the claim that during encoding and/or recall, the general knowledge base is used to guide the construction or reconstruction of a representation of the directly available information. During encoding, some information may be ignored, some may be transformed into an internal representation with consequent loss of the original form, and inferences made possible by the knowledge base may be added. During recall, missing or incomplete information may be added by inference, again according to the general seminal study of long-term remembering in which anomalous (at least to Westerners) passages were subsequently reconstructed in a transformed, culturally congruent theme. Further support for this assumption was provided by Bransford and Franks (1971) when they showed that adults cannot distinguish old sentences (ones originally presented) from new sentences that are semantically consistent with the old ones, indicating that the internal representation preserves meaning but not the original sentence structure. Landis (1982) has demonstrated a similar finding with children.

A more direct demonstration of the effect of pre-existing knowledge on comprehension and recall is the work of Brown, Smiley, Day, Townsend, and Lawton (1977). They showed that during recall of a previously presented story, older children's demonstrated intrusions were more semantically related to the theme of the story than those of younger children. The interpretation is again that older children have more knowledge of the themes and hence supply theme-related information that has been integrated with the representation constructed during comprehension. In another study that supports this conclusion, the familiarity of story characters, and whether or not they were behaving congruously with the children's prior knowledge of them, was manipulated (Ceci, Caves, & Howe, 1981). Again, the results demonstrated that long-term recall was quite accurate for familiar characters (such as the Bionic Woman) whose behaviors were consistent with the children's existing knowledge. However, both 7- and 10-year-olds' recall deteriorated considerably when they had to recall the actions of familiar characters who were described in the story in ways contradictory to the children's prior knowledge about them. This result again points to the role of children's prior knowledge and how it guides their systematic reconstruction during recall. Finally, this study also demonstrated that even 7 year olds were capable of making inferences when they possessed adequate content knowledge. They frequently inferred that feats of strength were committed by traditionally strong characters, e.g., Bionic Woman, when, in fact they had been committed by characters not known for their strength.

Constructive-memory researchers typically assess recall of what has been comprehended. Gobbo and Chi (1986), however, assessed construction in even a simpler task. They asked expert and novice 7 year olds—children who were either very knowledgeable or less knowledgeable in the domain of dinosaurs—to tell all they knew about individual dinosaurs when pictures of them were shown. Novices tended to describe only the explicitly presented features of each dinosaur. The expert children also described these features, but, in addition, gave detailed descriptions of the implicit features of the dinosaurs, such as their diet and habitat, even in cases where they were unfamiliar with a specific dinosaur. This finding suggests that the expert children were able to draw on their existing schemata of dinosaur knowledge to make inferences about traits of unfamiliar dinosaurs. Hence, this study shows that construction need not occur only in distorted recall, where memory is strained, but also can occur under circumstances in which a child is simply asked to look at a picture and describe it. Again, existing knowledge affects the amount of construction and the inferences the child produces.

D. PRACTICAL MEMORY

A fourth independent line of research is the study of memory in practical settings. Memory in practical settings presumably taps maximally motivated performance. The clearest illustration of motivated memory is the often-cited work of Istomina (1975), who showed that 3 year olds could remember twice as many items from a shopping list while playing "store" than they could in a more formal laboratory setting. This result can be interpreted in two ways, of course. The first is to attribute the high amount of recall to motivation, in which case developmental differences may still be maintained. That is, if adults were also given a shopping list, they could perhaps also double their recall. This interpretation is consistent with the informal observation that young children seem to excel at playing the game of *Concentration* because they are more motivated to win than adults.

The second interpretation of Istomina's data, which would implicate knowledge, is to say that a shopping list has some internal cohesion, and/or perhaps the list is somewhat redundant with similar lists in long-term memory. In other words, going shopping is much like activating a prestored script (such as eating in a restaurant), which includes several prominent items that are often purchased on a typical trip to the store (see Section V,D). This is essentially the view of both Mandler and Stein (1974), who showed an absence of age differences in recognition memory when the components were integrated into a cohesive scene, and Reese (1976), who demonstrated the utility of a coherent pictorial context on recall. Thus, some of the recall is based on short-term memory of the presented list and some is based on knowledge in long-term memory.

The role of an everyday familiar context on memory and cognition has not been adequately explained in the adult literature. For example, adults can accurately assess which cards need to be checked to verify a rule if the rule is stated in a familiar context (such as whether an envelope needs to be sealed as a function of whether a 3- or 5-cent stamp is used; Johnson-Laird & Wason, 1977). One interpretation is that a semantic structure already exists in memory for these everyday contexts, and ''reasoning'' becomes the instantiation of these internal representations. Viewed this way, the importance of knowledge gained from everyday experiences becomes critical in allowing a child to function optimally. In fact, Scribner (1977) arrives at this same view in her cross-cultural research. She found, for example, that even though nonliterate children and adults do not reason validly in the abstract, they do so if the inferences are embedded in the context of concrete real-world knowledge or appeal to personal experiences.

Similarly, Ceci and Liker (1986) have demonstrated that even individuals with low IQs can reason abstractly if the task relies upon their vast knowledge of sports or horse racing. As noted in Section III,B, in these experiments the complexity of the reasoning process was independent of IQ but highly related to factual knowledge. As Sternberg and Wagner (1985) have observed, expertise is less a matter of general aptitude than of domain-specific knowledge. An example of this can be seen in a study in which elementary school children were seated at a CRT and asked to predict the distance and direction that a dot on the monitor was likely to travel; they were to use an attached joystick to place a circle on the screen at the point where they predicted the dot would terminate. To correctly predict the impending distance, one must consider three variables interactively: the size of the dot, its color, and its speed. Not surprisingly, perhaps, children had trouble reasoning in terms of the required three-way interaction. They routinely failed to estimate the distance and/or direction traveled by the dot. Yet, when they were given what was essentially the same task (and a three-way interaction), except that it was reconfigured in a video-game format, they had no difficulty correctly predicting the distance traveled. In the latter task children were told to ''fire a missile'' at the likely location on the monitor where a spaceship (instead of a dot) would stop. This task required them to take into account the size, color, and speed of the spaceship in order to correctly estimate its likely distance and direction. Thus, both tasks ostensibly assessed children's ability to reason "multiplicatively." But the context was crucial: When it allowed children to call on their vast reservoir of video-game knowledge, they demonstrated greater complexity of reasoning than when the task was disassociated from their content knowledge. Of course, the role of motivation in producing this enhancement in children's reasoning cannot be ignored: Although performance at the video-game format was strongly related to the degree of children's prior experience with video games, as predicted by a "knowledge explanation," all children performed better on the video-game format, indicating a general motivational effect (Ceci, Bronfenbrenner, & Baker, 1987). Taken together, these findings suggest that world knowledge and personal experiences dictate whether logical inferences can be correctly deduced. The question remains, however, whether context-independent logical skills exist and, if so, whether they can be induced by everyday personal experiences since they are apparently not explicitly taught in schools.

E. ARTIFICIAL INTELLIGENCE AND EXPERT–NOVICE RESEARCH

A final force that might have influenced the thoughts of developmental researchers is the shift in cognitive science and artificial intelligence research from a focus on general strategies and control processes to domain-specific knowledge and procedures. (For a brief review of the broadening of emphasis to include the entire knowledge base relating to adult problem solving and artificial intelligence, see Chi, Glaser, & Rees, 1982.)

The earlier emphasis in artificial intelligence and cognitive science research was on the search for algorithms and other powerful heuristics and strategies for deducing and retrieving information. The techniques and theories that evolved, such as "means–ends analysis" in problem solving, and "rehearsal" in memory tasks, were intended to be independent of the particular knowledge base, and, as such, have proven to be valuable heuristics that are generalizable across different tasks and domains. However, the shift to a focus on the knowledge base was necessitated in part by the inability of both artificial intelligence and psychological theories to model human capabilities solely on the basis of search heuristics and memory strategies. These human capabilities, most dramatically uncovered in the chess research (Chase & Simon, 1973; DeGroot, 1966), showed that the adult experts excel on their tasks—playing chess, for example—not by virtue of more extensive and deeper search heuristics, but rather in their ability to code and remember chess patterns, which corresponded to having an extensive chess lexicon in memory. Even though the humans manifested a limited search procedure, in stark contrast to the essentially limitless search capabilities of the computer, the computer programs had great difficulty defeating human players. This finding pointed out the constraints of powerful search heuristics. This discrepancy soon compelled artificial intelligence researchers to develop theories and programs that took into account the role of the knowledge structure. This general trend in cognitive and artificial intelligence research clearly influenced many developmental researchers in their thinking about developmental issues in knowledge and cognition.

To summarize, the intent of this section is to briefly review the transition from a nonknowledge explanation to a knowledge explanation that can be witnessed in various findings in different domains, such as cross-cultural research, research in practical settings, and artificial intelligence research. Although the specific methods and factors that necessitated the shift in the interpretation may differ from one domain to another, the consensus seems compelling. However, it seems to have been much more difficult to convince developmental researchers that the content knowledge interpretation applies to developmental trends as well. For example, the developmental literature in causal reasoning in children is just beginning to emphasize the role of knowledge as a possible source of developmental improvement (Shultz & Kestenbaum, 1985). The reluctance to abandon the various alternative interpretations must be due to the robust and orderliness of the "stagelike" findings in children's cognitive performance. It is therefore much more logical to use a single parsimonious explanation such as a "stagelike transition mechanism" as a source of developmental change, rather than to identify various sources of knowledge that can account for the developmental trend. However, sometimes it is necessary to forego parsimony in the search of truth.

IV. Findings Implicating Content Knowledge as an Important Factor

Throughout the 1970s, many studies did implicate knowledge as a potential factor that could have explained the results, although often the researcher did not explicitly use the word *knowledge*. This section reviews specific studies which either indirectly implicated knowledge as an explanatory factor of developmental differences in memory performance (Section IV,A), or studies whose results could be interpreted from a knowledge perspective (Section IV,B), or studies which manipulated knowledge directly (Section IV,C).

A. FINDINGS THAT INDIRECTLY IMPLICATE KNOWLEDGE AS A CAUSATIVE FACTOR IN MEMORY PERFORMANCE

In this section, we review the studies of a few researchers who allude to an alternative factor to explain their results, and we interpret these alternative factors as knowledge related. In a majority of these studies, knowledge is implicated only by default, usually when the hypothesized source of developmental differences (e.g., strategic differences) seemed not to have played a significant role.

Three studies cited above, which appeared at the same time, all concluded that children's deficient performance on memory span and Piagetian-type tasks was related to the difficulties younger children had in encoding the relevant items. Having concluded from their data that temporal grouping did not affect children's memory span, Huttenlocher and Burke (1976), for example, suggested that "the limit on small children's span is explainable, at least in part, by difficulties in identifying incoming items and encoding their order" (p. 27). At one level, one might think that they have not explained anything, but have only stated what is needed to remember a string of items. However, what they are actively ruling out as an explanation of developmental differences in span performance is the role of a grouping strategy. Instead, they are attributing developmental differences to encoding or identification difficulties. Chi (1977) made a similar point when showing that children took significantly longer to name a familiar stimulus than adults did; furthermore, children took longer to recognize a stimulus than adults. Dempster (1981), in a comprehensive review of 10 sources of developmental differences in memory span, concluded that identification is the major factor accounting for developmental differences. Chi (1978) interpreted such differences in naming and encoding times to indicate that the amount and structure of knowledge stored in children's semantic memory impeded fast access to that information, but she made no attempt at that time to explicate how the structure of highly familiar information might preclude its fast access by a young child.

Siegler (1976) arrived at a similar conclusion in accounting for age-related differences on complex problem-solving tasks such as the balance scale problem. According to Siegler, younger children's use of more naive rules for determining which side of the balance beam will fall can be attributed to an inability to encode the relevant dimensions. Again, one might ask what is meant in saying that the child is unable to encode the right dimensions. In contemporary terminology, we might say that the child's representation or schema of a balance scale is incomplete, lacking some of the dimensions or variables of a mature schema of a balance scale. Hence, without an appropriate representation to encode the situation, the child would not know which dimensions to encode. Again, we could interpret the age differences in problem solving in terms of age-related differences in knowledge about the materials.

An excellent example of using knowledge development as an explanatory factor was demonstrated by default when Myers and Perlmutter (1978) could not explain why their 5 year olds recalled more information than their 2 year olds. Assuming that no memory strategies were used by either age group, they concluded that "given the lack of growth in deliberate strategic processes, memory development between 2 and 5 years of age may be attributed to increases in world knowledge derived from varied experiences and deeper levels of more extensive processing through the activation of more associated meanings'' (p. 214).

Similar post hoc invocations of knowledge as an explanatory factor were made by Ackerman (1982, 1983), and others (see Hagen, Jongeward, & Kail, 1975). These studies attest to the difficulty of accounting for observed age-related increments in memory in the absence of changes in either knowledge base or one's use of knowledge base. An excellent example of this difficulty is found in the study of retrieval variability posited to account for age-related differences in recall. Ackerman presented 7 year olds, 9 year olds, and college students words with accompanying input cues (e.g., *BIRD*–airplane) and input questions (e.g., ''Do they have wings?''). Later, the subjects were asked to recall the words (e.g., airplane), and they were provided with either a congruous retrieval question (i.e., congruous with their input question, such as ''Does this have wings?'') or an incongruous retrieval question (''Can this be eaten for dinner?''). Results indicated that the incongruous questions, which shifted the meaning of the cue words at the time of retrieval, penalized younger children more than the older subjects. These memory differences in children's retrieval deficits could be explained by the more limited semantic elaboration of the words at input. Thus, these researchers and others have come to the conclusion, a posteriori, that their findings might be explained as easily in terms of differences in the knowledge base, or the use to which the knowledge base is put, as in terms of their original hypotheses (e.g., differences in retrieval strategies).

B. FINDINGS THAT COULD BE INTERPRETED FROM A KNOWLEDGE PERSPECTIVE

In another set of studies, the results, although congruent with the specific hypotheses that the studies were meant to test, can also be interpreted to support a knowledge hypothesis. The reason is that variation in knowledge was not controlled developmentally.

A good example of such a study was carried out by Owings and Baumeister (1979). These investigators presented 7-, 9-, and 11-year-old children ''high frequency'' concrete nouns. The children were instructed to provide semantic (''What is it?''), phonetic (rhymes), or structural (''How many letters does it have?'') responses to each word. As predicted, semantic processing was highly effective at all ages, though more so for the oldest children. The investigators believed that this age difference was a reflection of older children's tendency to engage in more elaborate semantic encodings than the younger children (an encoding-skill interpretation), as the older children had spontaneously supplied more information about each word when it was presented. This encoding interpretation was favored over a strict knowledge interpretation because a second-grade teacher had rated all the words to be familiar to the youngest children. (Consistent with our previous analyses, the implicit assumption again appears to have been that because the words were familiar to the youngest children, they had equivalent knowledge but they did not typically generate it when the words were presented.) As the investigators argued:

> This hypothesis remains tenable despite the obtained age effects, because there were also age differences in the way people performed the incidental tasks. . . . Older children generated more comments about the words than did younger children. . . . This seemed to reflect a criterion difference rather than a knowledge difference: older people were more likely to define a word while younger people were more satisfied with simply saying something meaningful. (Owings & Baumeister, 1979, p. 108)

To test their hypothesis, Owings and Baumeister provided the same words to another group of children. This time, however, the experimenter supplied the semantic information for each word, and the child merely had to affirm or deny its accuracy. Thus, in order to equate the amount of information encoded, the experimenter provided identical encoding contexts for children of all ages. This manipulation was effective: Recall was essentially identical when the same encoding information was supplied for the youngest and oldest children.

Although Owings and Baumeister's results would appear to implicate encoding activity and not knowledge differences per se as a source of developmental differences in memory (given the presumed equivalence of knowledge), this interpretation is not without rivals. It can be argued, for instance, that by providing equivalent encoding information, the researchers may have unwittingly constrained the oldest children from engaging in their normal, elaborate forms of encoding. Evidence for this view can be found in the mean levels of recall in the experimenter-supplied versus child-supplied conditions: The provision of encoding information by the experimenter greatly aided the youngest children's recall but actually impeded the oldest children's recall (10% drop-off, from 52% to 46%). Thus, the distinction between an encoding explanation and a knowledge explanation appears unwarranted. Older children's superior memory was diminished by preventing them from encoding as much information as they might otherwise prefer. The results do, however, demonstrate the potency of knowledge: Increases and decreases in the encoding of information were linked directly to increases or decreases in the level of recall.

Taking a somewhat different perspective, Friedrich (1974) presented children from 7 to 17 years old associated and unassociated word pairs, dichotically. Overall, reliable age and semantic effects were obtained: Recall increased linearly as a function of age, and associated word pairs were recalled by children of all ages better than unassociated words. Neither of these findings is surprising. What is surprising, however, is the interpretation Friedrich attached to them. Because the older children outperformed the younger children on all tests even when various strategies were controlled, Friedrich maintained that the increases in memory with age were due, at least in part, to increases in storage capacity: "This conclusion is based on the following assumption. Given the use of the same strategy by children and adolescents, the finding that the latter group recalled significantly more information than the former reflects differential capacity limits" (Friedrich, 1974, p. 563). An equally parsimonious interpretation would be that the increase in recall with age was paralleled by increased knowledge with which to encode the words. As already argued, the selection of word pairs based on children's word association norms is insufficient as a means of equating for knowledge.

Clearly, the knowledge-base differences between younger and older children are enormous and researchers have great difficulty in finding materials that are equally well known to younger and older children (e.g., familiar faces, cartoon characters, games). As is demonstrated in Section IV,C, when researchers have equated for knowledge, previously observed age differences are often attenuated, if not abolished.

C. STUDIES WHICH MANIPULATE KNOWLEDGE DIRECTLY

Although all the studies cited in the preceding section either implicate the role of knowledge directly as a potential explanatory source for developmental differences or else can be interpreted that way, a few researchers in the mid-to-late-1970s directly called attention to the importance of greater knowledge as a source of developmental differences. Flavell and Wellman (1977) stated that

> Older individuals presumably store, retain, and retrieve a great many inputs better or differently than younger ones. They do so simply because developmental advances in the content and structure of their semantic or conceptual systems render these inputs more familiar, meaningful, conceptually interrelated. (p. 4)

Chi (1976) likewise stated that

> Another major difference that must be mentioned between children of different ages lies in the contents of long-term memory (LTM), especially the complexity of the knowledge base (semantic network). The knowledge base of a younger child can be limited in three ways. The first is the absence of a recognizable chunk. . . . The second . . . is in terms of the size of a chunk. . . . A third difference . . . is the number of associations, pathways, or test branches leading to a chunk. (pp. 563–564)

Perhaps in response to these solicitations to investigate the role of the knowledge base, several investigators during the same period actually tried either to control for age differences in the amount of knowledge or to manipulate it. Several attempts were made to directly equate in some manner subjects' knowledge of the stimulus materials, usually in terms of external measures of familiarity. Chi (1977) attempted to equate familiarity of the stimulus material by using faces of classmates, so that both the adults and children had an equivalent number of years of exposure to the faces. Faces were used not only because they permitted a global measure of familiarity, but more importantly, because successive faces are not recodable into a single chunk, that is, each face can only be one unit of information with which one can assume that children are familiar, given that the faces are those of their classmates. By avoiding sequencing faces of close friends or siblings, one can prevent the chunking or recoding of pairs or subsets of faces into a meaningful unit. Hence, in developmental research, one has to be concerned with familiarity with each individual item, as well as the recodability of a string of items into a chunk. These two measures of familiarity usually cannot be simultaneously controlled when the stimulus materials used consist of items such as digits or letters (Boswell, 1974; Dempster, 1978). However, when individual item familiarity is controlled, as in the case of familiar faces, the results showed that age differences were reduced.

In two other studies, the converse manipulation was used. That is, stimuli that were presumably equally unfamiliar to adults and children were used. Both Boswell (1974) and Dempster (1978) controlled for stimulus familiarity on a memory-span task by using consonant letter strings that had little structural similarity to English. In Dempster's study age differences disappeared between 6 year olds and 11 year olds. Boswell used a slight variant of the span task, in which the stimuli were exposed very briefly. The result of this study was that age differences between 7 year olds and adults declined as a direct function of the degree to which the letter strings departed from familiar English words. Although age differences in Boswell's and Dempster's studies were reduced, they usually were not completely eliminated. As we stated above, one of the problems may be that even though the stimuli were chosen in such a way as to prevent recoding, one still has to be concerned with familiarity of each individual item. In Chi's (1977) study cited above, even though the children and adults were assumed to be equally familiar with the faces of their classmates by equating for the number of years of exposure to the faces, item familiarity was still found to differ when it was measured by a more sensitive index, such as stimulus identification time. Using a very brief stimulus exposure followed by a mask, Chi (1977) found significant differences in the exposure durations needed for children and adults to identify a face (139 msec vs. 26 msec). The point is that in both the Boswell (1974) and the Dempster (1978) studies, even though the letter strings were not chunkable, younger and older children clearly had different amounts of familiarity with the individual letters, which could produce significant differences in encoding times and thus result in age differences.

Another concern is the virtual impossibility of controlling the type of mnemonic association adults employ to convert meaningless material into something meaningful (Prytulak, 1971). Richman, Nida, and Pittman (1976) and Ceci (1980) attempted to control for the amount of semantic knowledge by equating the meaningfulness values of words. As mentioned earlier, research on the meaningfulness of words has indicated large age differences, with adults generating many more associates than children (Emmerich, 1979). In this vein, Richman *et al.* showed that when the same words were used for different age groups in a verbal learning task, older children learned more rapidly than younger children. However, when different words were used for each age group so that meaningfulness values were held constant across grades, between-grade learning differences were minimal. Such results led Emmerich (1979) to conclude that:

> Although adult-derived values of picturability and concreteness may be useful when studying learning and memory in children, meaningfulness values should be based on child-derived norms. Indeed, meaningfulness values probably vary as a function of age even within the elementary school age range. (p. 465)

The meaningfulness of a word can be interpreted as the richness of the semantic interconnections in the knowledge base surrounding that word concept. Holding meaningfulness constant implies the absence of knowledge differences, and hence age differences in learning performance should be minimized. This is precisely the finding obtained in a free-recall task when Ceci (1980) gave extensive semantic training to 4 year olds. While controlling for item exposure, he was able to show that recall of a long list of animals increased as a linear function of the number of interconnections among the animals. An important finding of this study was that older children possessed sufficient knowledge to form interconnections among various animals that are ostensibly unrelated (e.g., platypus and anteater both eat insects), but younger children required experimenter-provided knowledge to connect them ("They both lay eggs"). Such differences in the way interconnections are provided are not related to age per se, since Chi and Koeske (1983) have shown that, for a 4 year old child, knowledge of familiar dinosaurs was more interconnected than knowledge of less-familiar dinosaurs. For example, the child could say that stegosaur and allosaur both eat meat but not that two relatively unknown dinosaurs eat meat.

Similarly, when the amount of semantic knowledge children have of words was controlled in a cued recall task, no differences in recall scores were observed between 7 year olds and 12 year olds (Ceci & Howe, 1978b). Taken together, these studies suggest that semantic knowledge is a very important factor in memory performance and, furthermore, that age-related differences in semantic knowledge are often important sources of developmental differences.

Besides equating for the amount of knowledge across ages, one can also manipulate the knowledge children and adults have. For example, Chi (1978) compared the performance of adults and 10 year olds on digit span and memory for chess positions. Chess knowledge was assessed by an external indicator (the speed with which subjects completed a Knight's Tour Task), and the 10 year olds were found to be slightly more knowledgeable than the adults. A crossover effect was obtained in which the 10 year olds could recall a greater number of chess pieces from game positions than the adults, but at the same time they could recall fewer digits than the adults. This finding has been replicated using other stimuli. For example, using words from the Battig and Montague norms for adults and a list of cartoon names and children's games which was originally generated by children, Lindberg (1980) obtained the same crossover effect in recall. At the other end of the age spectrum, the same crossover effect was found by Barrett (1978) in recall for a list of nouns generated by young adults versus nouns generated by older people. Both groups were told to generate nouns with which they felt people of the other generation were unfamiliar. Likewise, Worden and Sherman-Brown (1983) manipulated word frequency by using old-versus-recent word norms and showed that older adults have superior retention of words that were popular in their youth (e.g., *swell*) than for more recently popular words (e.g., *stress*). Clearly, as Bjorklund and Thompson (1983) also indicated,

> The degree of knowledge children possess . . . can have important consequences for performance on memory tasks. To elaborate, children often demonstrate an enhanced level of recall when memory is assessed in tasks using materials that are meaningful and well known to *them*, in comparison to when more traditional materials (i.e., items which are more familiar to adults) are used. (p. 341)

In summary, this section reviewed earlier research which implicated knowledge as an explanation for their results, even though ostensibly the developmental differences were attributed to encoding differences. Another set of studies provided results that were consistent with both a knowledge interpretation and an alternative one preferred by the individual investigator (such as capacity differences). Finally, contemporaneous studies also existed which manipulated the amount of knowledge children possess directly. These studies tend to show that developmental differences are reduced when the amount of knowledge is somehow either controlled or equated. Thus, within the domain of memory development research per se, the role of knowledge was emerging and taking on a prominent role in the late 1970s and early 1980s.

V. Assessing the Representation of Content Knowledge

By the 1980s, cognitive developmentalists appear to have been convinced that content knowledge plays a critical role in cognitive development. However, saying that young children have less knowledge than older children or adults borders on triviality. The sheer quantity of knowledge, although important, is not nearly as important as how that knowledge is structured. Hence, the focus of the 1980s is on (1) how children's knowledge is represented, that is, the structure of that representation; (2) how the structure of children's representation compares with adults' structures; and (3) how the structure within a representation affects processing performance. Questions 1, and 3 are issues that concern adult cognition as well. There are additional issues that concern developmentalists, such as whether children have and use different kinds (or modes) of representations. In the following paragraphs, we attempt to clarify some of these terminologies as well as introduce our theoretical notions.

The word *structure,* as used here, can refer to either the degree of organization within a given representation (something that is quantifiable, as is shown in Section V,A), or it can refer to something qualitative and manifested usually in terms of how knowledge is used in performing a task (as can be seen in the research discussed in Section V,B, C, and D). There are many other terms that developmentalists often use, such as the *content, mode,* and *format* of a representation. We should at this point relate what we mean by *structure* to these other terms. The content of a representation is the information that the representation contains. To be more specific, Fig. 1 is an idealized hypothetical representation (a network) that we can choose to illustrate some of the points. The content of this representation refers not only to what concepts (the circles) and attributes (the triangles) are contained in a given representation, but also to the links (lines connecting the concepts and attributes). Hence, when people maintain that children acquire more knowledge as they develop, they are generally referring to an increase in the amount of information contained in a representation. In this case, they would be referring to the number of concepts, or the number of attributes related to each concept. Hence, *what* knowledge children have simply refers to what concepts and attributes are contained in their memory. One could also say, although people make much less reference to this, that children's knowledge increases as they acquire more links among the concepts and attributes that they already have. One could interpret Rozin's (1976) theory of access in this way also. That is, with development, knowledge becomes more accessible because there are more links interconnecting the different components of knowledge. (See Section VI for more discussion.)

The *mode* of a representation generally refers to the nature of the internal code of a representation, for example, whether it is in the form of images or propositions. There is a general debate among adult cognitive psychologists concerning whether our internal representations take the mode of images or propositions. Developmentally, however, the issue has been whether a child shifts from a more image-like representation to a more proposition-based representation. This is not an issue that we are concerned with in this article. We confine our discussions to propositional-type representations.

We use the word *format* to refer to a kind of formalism a researcher uses in describing his representation. Besides a network, which is commonly used to represent declarative knowledge, a production system is a kind of format that is

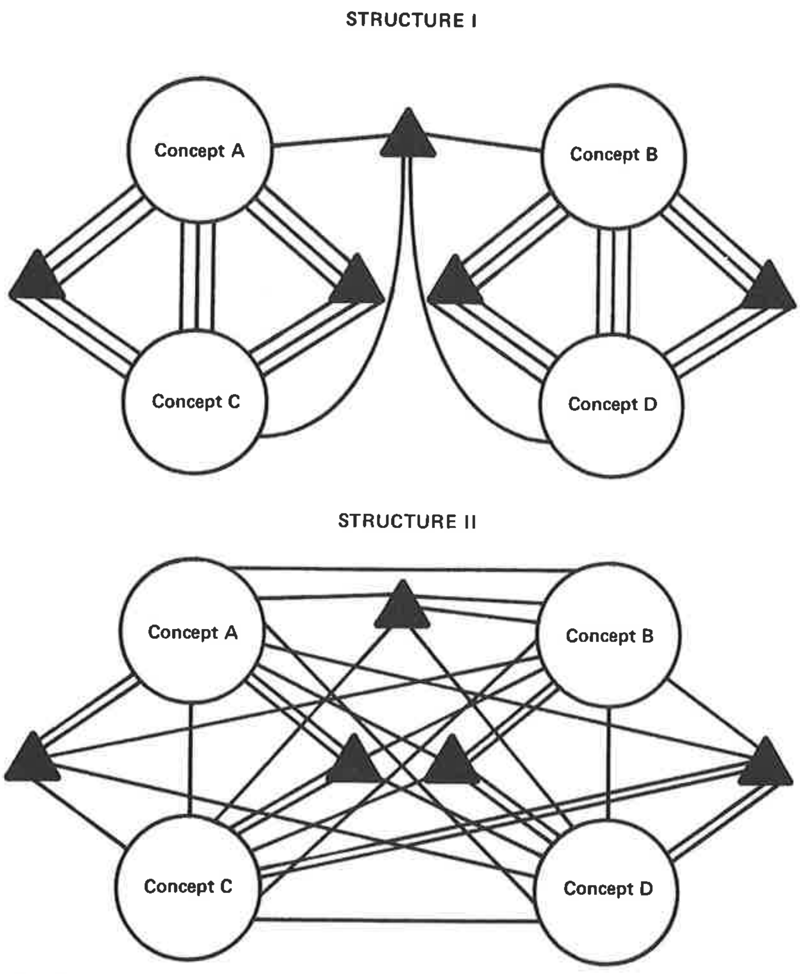

Fig. 1. An idealized hypothetical representation of two structures that have the same number of nodes and links.

commonly used to represent procedural knowledge (Young & O'Shea, 1981), and planning nets would be a different format (VanLehn & Brown, 1980).

Once a particular format is chosen, we can discuss the "structure" of that representation without discussing the content or mode. In Fig. 1, both the top and the bottom representations have the same number of concepts, attributes, and links. However, because the concepts and attributes are linked in different ways, one could say that one structure is "better" than another (or more well defined), and the performance corresponding to one structure is better than the other. For example, one might define Structure I in Fig. 1 to be better in that it clusters Concept A with Concept C and Concept B with Concept D through the sharing of attributes. Thus, Structure I has two higher order clusters that are not apparent in Structure II. The two networks in the Chi and Koeske (1983) study illustrate this point. Hence, when we ask (in Question 1 above) what the structure of a representation is, we really mean what is the pattern of the linkages which may create clusters or other types of higher-order units. When we ask, as in Question 3, how the structure within a representation affects processing performance, we would have to demonstrate that one structure is more facilitating than another structure. For example, the child might recall with greater clustering if his knowledge corresponded more with Structure I than Structure II (Chi, 1985), or the child who has Structure I knowledge might make more inferences about new concepts that fit into the cluster of Concepts A and C. In the Gobbo and Chi study (1986), for example, we found that expert children generally are more able to infer attributes about unknown dinosaurs than novice children, suggesting that the expert children have more well-defined clusters with which they can generate inferences about unknown dinosaurs that fit their clusters. A study by Chi and Robin (1986) investigates whether expert children are more able to make these inferences if the new concept fits well with their existing family clusters. That is, if a new Concept E is similar to Concepts A and C, they are able to infer attributes about it, but if Concept E fits neither the Concepts A–C cluster nor the Concepts B–D cluster, they may not be able to infer any attributes about it, much like someone (a novice) who has a representation as in Structure II of Fig. 1.

We begin this discussion by choosing a representation (a network) that we like to work with. Many people prefer to use different kinds of propositional-type of representations, such as feature lists (Rosch & Mervis, 1977), dimensions (Reed, 1972), or conceptual graphs. Which kind of representation researchers use depends of course on what their needs are. But in particular, it can also depend on how quantifiable the representation is. For example, it is much more straightforward to measure the organization of a representation in terms of a dimensional analysis (as is shown in Section V,A) than in terms of a network or script representation (Sections V,C & D). The trade off, unfortunately, is that in a more easily quantifiable representation there is less one can learn about knowledge organization than there is with one that is difficult to quantify. In fact, a major issue is how one can measure the structure of knowledge representation when it concerns complex knowledge.

In the remaining portions of this section, we concentrate on studies which use propositional representations to represent children's and adults' knowledge of concepts and events. The issue is in what ways the representations are similar or different among children of different ages. In the first section we review work concerned with dimensional representations; in the second section, categorical knowledge; and in the third and fourth sections, the scant amount of developmental literature on structural representations of concepts and events.

A. MULTIDIMENSIONAL SCALING AND CLUSTERING STUDIES

A common way to uncover the underlying structure of conceptual knowledge is to use multidimensional scaling techniques to determine the dimensions children of different ages use to represent knowledge. The actual method of gathering data can range from pairwise comparisons of similarity to oddity tasks where the "odd" member of a three-member triad is selected. These data provide measures of psychological distance between two concepts. The psychological distance is seen as some function of one or more features shared by the two concepts.

Studies of the semantic structure of animal terms in adults, for example, have typically revealed two-dimensional representations that can be interpreted to be size and ferocity (Rips, Shoben, & Smith, 1973). Storm (1980) also found size to be a prominent dimension for adults, with the second dimension being habitat (land or water). The inconsistency across studies in the dimensions found for a given age group (adults in this case) may be a function of both the specific animal terms used as stimuli and the fact that dimensions have to be interpreted by the researcher.

Two general developmental findings emerge from this literature. The first is that older children tend to have dimensions that are more abstract (e.g., "valuable" animals); the second is that older children tend to have some dimensions that younger children lack. Howard and Howard (1977), for example, suggested that as children mature, the size dimension becomes less salient, and the domesticity dimension becomes more salient, suggesting a developmental shift from perceptual to more abstract dimensions. Bisanz, La Porte, Vesonder, and Voss (1978) conducted a study which also supported the conclusion that younger children may lack certain dimensions. They studied recall of a story containing two separate themes, one about helpfulness and the other about leadership, and found that the younger children's recall consistently missed the component of leadership, but the older children did not. Although ideally one would want to have an independent assessment of whether the dimension of leadership was in a child's repertoire, this finding is consistent with our interpretation that when the existing knowledge base does not contain the concept of leadership, young children will have difficulty encoding it during comprehension. Thus, our hypothesis in the previous section concerning encoding deficiency and its ramification in the knowledge base can be somewhat substantiated by the conjunction of these two results.

Another interesting variant of a factor-analysis approach is to have children rate familiar television characters along concrete dimensions that the children explicitly supply (e.g., strong, attractive, nosy, smart). The aim of this manipulation is to determine why children's recollections about some familiar television character's actions and motives are distorted and others are not. For example, a frequent observation is that the youngest children (6 to 7 year olds) allege that someone other than Lieutenant Columbo solved a crime that in fact had been solved by Lieutenant Columbo. Similarly, 6 to 7 year olds often diminished Mr. Spock's problem-solving prowess. At first, these apparent misperceptions were baffling, but they became understandable only when young children's ratings along the dimensions they had provided were factor analyzed. Although young children could supply several dimensions (such as strength, attractiveness, nosiness, intelligence) on which to compare or describe a character, these dimensions all contributed to a single good–bad dimension. That is, over 70% of the variance could be accounted for by the single good–bad dimension: A good person is someone who is strong, attractive, not nosy, smart. These dimensions are therefore correlated. Thus, for the youngest children, the implication of being unattractive is to be weak and stupid. Given that Lieutenant Columbo was rated as unattractive (presumably because of the common knowledge among British children that the actor Peter Falk possessed a glass eye), he thus must necessarily possess the other attributes (weak and stupid) of their single dimension. Older children, however, had knowledge structures that were considerably more differentiated. Ten year olds, for example, could construe someone as strong and smart, yet unattractive (Ceci *et al.*, 1981).

In a related research approach, clustering analysis (rather than multidimensional scaling) is used to express the relationship among a set of concepts in terms of a hierarchical tree structure. Sorting data, free association, and other kinds of rating data can all be subjected to a clustering analysis. The difference between clustering analysis and multidimensional scaling is that clusters may be based on shared features that are not necessarily applicable to all items. (That is, unlike multidimensional scaling wherein all items must be assigned values on all dimensions, clustering analysis segments a list of items into groups that have overlapping features.) Again, though, subjective interpretation must be provided for the clusters. (Subjective interpretation can present an especially thorny statistical problem, because cluster analysis, by its nature, yields clusters—even among randomly generated stimuli. Recently, a number of "validation" procedures have been developed to ensure that clusters reflect psychologically important structures, not random configurations.) An additional characteristic of cluster analysis is that it also permits assessing the degree of clustering: low "proximity" values indicate weak associations.

There are basically two general developmental findings: the degree of association tends to be weaker and more idiosyncratic in younger children, and the nature of the clusters tends to be more perceptual. This is essentially what Storm (1980) found for animal terms. For example, for 12 year olds, the two major clusters at the highest node were based on size, a perceptual feature, but zoologists divided their major clusters on the basis of food habits (herbivores and carnivores). For the youngest children (5 year olds), however, no systematic interpretation of the clusters was possible. Storm provided two potential explanations for the lack of systematicity. One was that if the dimensions used were primarily perceptual, then many features could be used and the specific ones that the children focused on might not be obvious to the experimenters. The other explanation could be that either no child applied any criteria systematically, or each child applied criteria systematically but individual children applied different criteria.

We would like to elaborate on the second explanation, that is, why children may not use one or two dimensions consistently to determine class membership. Based on some of our own data (to be discussed later, Gobbo & Chi, 1986), we conjecture that the inconsistency arises from an incoherent knowledge structure rather than an idiosyncrasy in the sorting behavior. That is, the youngest children do not use one or two consistent dimensions to determine class membership because their knowledge of the concepts lacks complete specification by a consistent set of attributes. By examining the way expert and novice 7 year olds identified class membership (meat- or planteater), we found that the expert children could (but the novice children could not) use the presence or absence of a specific feature in an inclusive and exclusive way to determine class membership. For example, a dinosaur must be a meateater if it has sharp teeth and a planteater if it does not have sharp teeth. Novice children tend to use the presence of different sets of features to determine diet categories. The implication is that when children do not have rich knowledge of a domain, they cannot use a consistent set of attributes or dimensions to contrast two classes or categories. Consequently, their cluster analyses are more difficult to interpret. This suggestion is also consistent with Ceci's (1980) data cited earlier in Section IV,C. That is, older children, who presumably have greater knowledge, can supply their own relations for platypus and anteater, but younger children cannot. When children have a great deal of domain knowledge, their sorting behavior is more consistent and interpretable (Chi, 1986; Gobbo & Chi, 1986).

In conclusion, the review of the literature suggests that younger children generally have fewer features or dimensions with which to represent concepts. One alternative hypothesis is that all the features or dimensions are present, but they may simply not be very salient or readily accessible to the child. For example, the aggressiveness or dominance of an animal may not be a very salient feature, that is, not readily accessible, to the child. This hypothesis is consistent with Smiley and Brown's (1979) data showing that even though younger children spontaneously chose pairs of items on the basis of thematic membership, they could, when probed, justify an alternative pairing on the basis of taxonomic category. Thus, one need not assume that younger children lack the information concerning a particular feature such as aggression; rather, one could assume that such a feature was not salient or not readily accessed. Finally, even if a particular feature of a semantic relation exists, there may still be a developmental trend in the subtlety of the feature (Landis, Herrmann, & Chaffin, (1984). For example, adults demonstrate an awareness of the distinction between *contrast* (e.g., hot–cold) and *contradiction* (e.g., dead–alive). The former can be qualified by modifiers, such as *more or less, very,* but the latter cannot. Adults therefore can use such distinctions in solving analogy problems whereas children may have difficulties.

B. CATEGORICAL KNOWLEDGE

Researchers who study the structure of categorical knowledge ask what members are contained in children's and adults' categories. The research goal has been direct assessment of the structure and content of children's categorical knowledge. The evidence accumulated so far indicates that the structure of children's categories is fundamentally the same as adults', except that it may be more restricted. That is, children do have basically the same categories and the same set of "core" or "typical" items (Mervis, 1980). What may differ is the extent of the categories. The category boundaries of young children may be more restricted and less well defined. Several studies support this inference. For example, Saltz, Soller, and Sigel (1972) asked children to select exemplars of categories from a large set of pictures. Exemplars that were picked by 75% of the children were considered to be the core or typical members of a category. A frequent finding was that the younger children's core members were a subset of older children's core members. Rosch (cited in Mervis, 1980) asked subjects to indicate the truth of sentences such as *A dog is an animal.* Both children and adults were faster at responding to such sentences if the item was a typical exemplar of the category (as determined from word association data) than if it was not. Furthermore, children made more errors in verifying atypical exemplars than typical ones, suggesting that children have already learned the typical but not the atypical exemplars (Bjorklund & Thompson, 1983, reached a similar conclusion). Nelson (1974) asked children to generate instances of a superordinate category such as animals. She found that 5 and 8 year olds generated predominantly the same set of core items, except that the younger children produced (1) fewer exemplars for each category, (2) more inappropriate instances of a category, and (3) a more limited set of core items than adults. (Rosner and Hayes (1977) obtained similar findings.)

In sum, a fairly safe conclusion is that young children have fundamentally the same contents of categories as older children and adults, with the differences being that their categories are more limited in members and contain fewer core items, and the boundaries are less well defined.

Having reached this conclusion, one should wonder about the discrepancy between the apparent availability of categorical knowledge in young children and its similarity to the adult categorical structure, and children's apparent lack of the adult dimensions (Section V,A), or their failure to use this categorical knowledge in sorting and clustering performance (a deficiency that is often attributed to lack of a skill or strategy). This apparent discrepancy has been discussed in detail elsewhere (Chi, 1985), but to summarize briefly, this discrepancy can be resolved if one assumes that young children can sort, classify, and cluster fairly consistently if the core or typical members of categories are used. In other words, if the experimenter uses members of a category that are available to the child, the child is more likely to sort, classify, and cluster on the basis of taxonomy. Evidence for this assumption can be gathered from research on "high and low associates," "typical and atypical exemplars," "subject-generated members," "core members," "highly representative members," and so on (Bjorklund, Thompson, & Ornstein, 1983; Carson & Abrahamson, 1976; Corsale, 1978; Haynes & Kulhavy, 1976; Moely & Jeffrey, 1974; Nelson, 1969; Northrop, 1974; Rabinowitz, 1984; Rossi & Rossi, 1965; Worden, 1976). This evidence is convincing in showing no real discrepancy between the availability of categorical knowledge and performances on tasks such as clustering or sorting, if a distinction is made between children's performance on the more typical members versus the atypical members of their categories. Thus, we believe that one cannot make any inferences about children's ability to perform skills such as classification without addressing the issue of the interaction of these skills with content knowledge. This same point has been made emphatically in the work of cognitive anthropologists (Lancy & Strathern, 1981), as well as in our own work that was described in Section III,B (Ceci & Liker, 1986).

Research on the representation of categorical knowledge is addressed not only to the contents of the categories, but also to the issue of hierarchy. That is, perhaps children have a more developed representation at a less superordinate level than adults and thus can exhibit adultlike classification performance at a lower level. That is, linkages may connect many of the members of young children's basic categories with the basic concept, whereas few linkages may be present at the higher level. For example, children tend to know early that high chair and rocker are kinds of chair but they may not have acquired the knowledge that chairs and lamps are kinds of furniture. Again, this approach focuses on the same distinction between skill deficits and knowledge deficits. The hypothesis here is that children can exhibit sophisticated hierarchical classification if their performance is assessed at a lower level in the hierarchy, where their knowledge is more complete. This is a reasonable expectation given that children do acquire word meanings and concepts at the basic level first (e.g., chair) and only later at the superordinate level (e.g., furniture) (Rosch *et al.*, 1976; Mervis, 1980).

These expectations generally have been confirmed. For example, one would expect children to be able to name basic-level concepts before learning to name superordinate concepts. This expectation seems to be confirmed when one analyzes a child's early speech (Rosch *et al.*, 1976). Another implication of the prediction is that young children should be able to sort the basic level objects. Rosch and Mervis (1977) found that young children can put together two pictures (out of the three) that go together, if these objects are selected from the same basic level. These data are consistent with earlier data of Schaeffer, Lewis, and Van Decar (1971), although they did not present their work within a categorical representation framework. Children can also learn to sort artificial stimuli fairly easily if the stimuli are constructed with the constraints of basic level objects (Horton & Markman, 1980). Finally, novice children (without much knowledge of dinosaurs) can sort dinosaurs fairly adequately if one assumes that families of dinosaurs (i.e., those whose members share a relatively large number of attributes) are the basic level categories. This assumption is supported by evidence showing that expert children (those with a great deal of dinosaur knowledge) can sort at more abstract levels, such as the dinosaurs' food habits (Chi, 1985; Gobbo & Chi, 1986), while novice children of the same age tend to sort on the basis of more perceptual (basic-level) features. One can argue that food habits (plant- or meat-eating) are more abstract because (1) they are the two superordinate categories that zoologists use to classify animals (Storm, 1980); (2) the two food-habit categories subsume the family distinctions, thus making them to be the more inclusive categories; and (3) they are generally inferred from visible perceptual features such as large, sharp teeth.

C. NODE-LINK SCHEMA

Several lines of research have been focused on different aspects of representations of concepts. The generic class of mental representations or structures of knowledge which guide both the interpretation of input information (including the generation of expectancies and inferences) and the retrieval of that information is known as a *schema* (Adams & Worden, 1986; Rumelhart & Ortony, 1977; Schank & Abelson, 1977). Schemas have been subdivided, depending on the domain: *stereotypes* refer to schema for the interpretation of person types, *scripts* refer to schema that are involved in the interpretation of frequently enacted events that possess a known temporal or logical order, and *node links* refer to schema that underpin the organization of a concept's semantic/lexical features. In this section we focus on node-link schema, and in Section V,D we discuss the development of scripts.

Much of the research that has been consistent with a node-link framework has concerned the presence or absence of certain hierarchies, in particular, taxonomic or class-inclusion hierarchies. A good early example of this research is the work of Schaeffer *et al.* (1971), who postulated that superordinate semantic nodes (e.g., animate and inanimate) are acquired later in life than the subordinate nodes, such as plants, animals, vehicles, and utensils. To support their postulates, they asked children to select the odd member of a triad. Younger children were predicted to make errors on problems in which a superordinate node had to be accessed for judgment of similarity (e.g., cow, fork, tree). As predicted, 6 year old children made many more errors when the discrimination had to be based on an animate–inanimate distinction than when it had to be made on the basis of a plant–animal or vehicle–utensil distinction. As mentioned in the preceding section, we now know that the reason is that young children's knowledge is more fully developed at the basic level than at the superordinate level. Fourteen year olds, although their accuracy was greater, exhibited basically the same pattern of results, that is, better discrimination of plant–animal than animate–inanimate distinctions. Hence, one could argue that young children do not lack a hierarchical structure entirely, but rather their hierarchy is perhaps less reliable and contains incomplete information.

Schaeffer *et al.* (1971), however, denied that a real hierarchy exists in the sense that inferences from class inclusion can be drawn. To support this belief, they argued that although children found it easier to deal with animate than inanimate entities, children do not necessarily deal with plants and animals more easily than with vehicles and utensils (perhaps because animate objects share a set of well-defined attributes and inanimate objects do not). This pattern of results was interpreted by the researchers to suggest that subordinate nodes were not combined to form superordinate elements. (That is, the subordinate nodes have some kind of localized coherence and a hierarchy need not exist.)

More recently, however, a few other researchers have used nontraditional techniques to uncover the hierarchy or at least the presence of superordinate nodes. An example is the presence of overextensions in very young children's speech productions when basic-level words are used to refer to superordinate categories. One could also interpret very young children's looking time to indicate the existence of a superordinate class. Ross (1980) assumed that children will look longer at objects from the superordinate categories than the basic categories, because items from the superordinate categories should have greater perceptual dissimilarity and thus produce greater interest for very young children. The presence of a specific hierarchy has also been investigated in other interesting ways. Keil (1981) has shown, for example, that preschool children's categorical representation is hierarchical, on the basis of the way they make judgments about the anomalies in the application of certain predicates to various terms. For example, certain predicates can be applied only to humans (such as *is sorry*), and others can be applied only to all living things (such as *is dead*). Hierarchy is preserved because predicates appropriate at a given level in the hierarchy were considered to be anomalous when applied to any term higher in the hierarchy. Chi (1985) has also suggested that by looking at pauses in young children's speech productions, we can partition the outputs into hierarchical chunks. Hence, in both the clustering types of analyses and these other types of work, we can tentatively conclude that children's knowledge is often organized hierarchically.

A second issue of a network representation concerns the precise representation of a given concept in terms of what features of each concept are acquired with development. Clark's (1973) Semantic Feature Hypothesis is a good example of this type of representation, where the acquisition of word meaning is seen as the addition of features of meaning to each lexical entry of a word. Using a network model to represent the meanings of verbs such as *buy* and *take,* Gentner (1975) has shown that young children's order of acquisition of verbs is predicted by the number of specific components. For example, the complete meaning of the verb *buy* is acquired much later than the meaning of *take* because it has additional components, one of them being the idea of an obligation to transfer money.

A third issue in the representation of concepts, which is absent in the featural lists approach and the dimensional approach, is the relationship between different aspects of the concepts. A semantic network captures the interrelationships among different concepts and aspects of a given concept. Several motivations exist for pursuing the notion of a network, besides the need for a detailed structure of knowledge about a single concept (e.g., in the work of Clark, 1973, and Gentner, 1975, mentioned previously). The associative nature of knowledge needs to be represented, as well as the notion that knowledge is organized into units or packages (Rumelhart & Norman, 1986). These two aspects of knowledge representation seem particularly salient in understanding developmental findings. We agree with Farah and Kosslyn (1982) that "it seems that virtually no work has been done on the organization of children's concept representations" (p. 161).

We have attempted in some of our own research to depict the interrelationships among concepts and the organizational "packages" in children's knowledge representation. Our most direct effort has been an attempt to depict children's knowledge of dinosaur concepts, and how the pattern of interrelationships among the dinosaurs can predict recall patterns (Chi & Koeske, 1983). In order to represent a child's knowledge of dinosaurs, we used two sets of production data. First, we took the child's freely generated set of dinosaur names over multiple trials and sessions and looked only at the associations among successive names generated within a 10-sec pause. That is, if the child generated Dinosaur A followed by Dinosaur B, we denoted this relation by a link in our network. The strength of a link between two dinosaur concepts was then determined by the frequency with which these two concepts were produced together in a free-generation task. Second, the child was asked to identify (recognize) as well as to generate (recall) attributes of any given dinosaur. Features that were either recognized or recalled by a child were depicted as attributes linked specifically to a dinosaur concept. To avoid redundancy, we took the liberty of associating the same attribute node to two dinosaur concepts if the same attribute was mentioned in relation to both dinosaurs. The mappings of our networks were basically guided by fundamental assumptions of network models, such as the notion of spreading activation, strength of links, and the nonredundant storage of memory nodes. Once the networks had been mapped for two sets of dinosaur concepts (one set of 20 included those about which the child was quite knowledgeable; the other set of 20 included those about which the child was less knowledgeable), we imposed hypothetical groupings on subsets of dinosaurs to represent the idea of ''packages'' of knowledge. Our groupings corresponded to the ways the dinosaurs were introduced in the books that were read to the child. Because the groupings were unitizations that we imposed, we had to seek external evidence of their validity. To do so, we examined the pattern of linkages within and between these group boundaries.

We defined two measures of cohesion, or indicants of stronger within-grouping relations as compared to between-grouping relations. One measure was the strength of the linkages among dinosaur concepts. Indeed, we found that dinosaur concepts within a group showed multiple direct (dinosaur–dinosaur) links but either no direct or only a single link to dinosaurs in other groups. A second measure was the amount of sharing of attributes, or dinosaur–attribute–dinosaur links. We found a greater number of these indirect links within a group than between groups. Thus, although the hierarchical groupings were imposed by us, we felt that the pattern of interlinkages within and between these groupings provided some evidence of their validity. Such patterns of differential interlinkages were not apparent in the set of 20 less-familiar dinosaurs. This finding suggests that one outcome of acquiring greater knowledge of a domain may be the formation of well-defined hierarchical groupings.

In fact, comparing the mappings of the less-familiar set of 20 dinosaurs with the mappings of the more-familiar set of 20 revealed several facts we can speculate about regarding what develops as a child acquires greater knowledge in a given domain. First, the child undoubtedly acquires a greater number of attributes about each dinosaur. Second, greater familiarity manifests itself in the strength of the links. Comparing the links of the more-familiar set with the links in the less-familiar set clearly showed that a greater number of dinosaur concepts in the more-familiar set had stronger links than the concepts in the less-familiar set. Third, and most important, is the clear formation of strong cohesive groupings in the more familiar set.

We would like to suggest, of course, that differences in the two representations produced the differential recall and forgetting observed (Chi & Koeske, 1983), as well as the differential sorting (Chi, 1985). The child had no difficulty sorting the familiar dinosaurs into the plant-eating and meat-eating categories, the precise two groups that are reminiscent of the zoologists' categories in

Storm's (1980) data. The child's sorts of the less-familiar dinosaurs, in contrast, were erratic, inconsistent, and unstable over three trials, and in this respect were very characteristic of young children's sorting in general.

Notice that our approach to the construction of semantic networks is distinct from other approaches (such as Gentner's) in that our networks are created from protocol data. Thus, the resulting patterns of interlinkages are structures that emerged from the data. In other approaches, the researcher typically constructs a network from theoretical assumptions, and the network is then used to predict performance measures such as acquisition sequence, onset of use, reaction time in sentence verification, and so on.

D. SCRIPT REPRESENTATION

Like research based on other types of schematic representation, research aimed at uncovering children's knowledge represented in the form of scripts also requires the assumption that children and adults have the same form of representation. The issue is to what extent the content and structure of the scripts are different and how such differences might affect performance.

The major difference between research focused on the type of schemata discussed in the previous section (node links) and research dealing with scripts is in the unit of knowledge being explored. The previous schema approach, at least as it is used in the research described in this article, tended to focus on the representation of concepts. Scripts, in contrast, have been used to represent events that involve temporal sequences, such as going to a restaurant. Like the other schemata, a script representation has a set of expectations about what will occur and when it will occur in any given situation. The issue that concerns developmental researchers is whether young children use these scripts in representing and interpreting the world in much the same way that adults do, that is, do scripts of children represent the world in the same way as adults' scripts.

Nelson and colleagues have carried out a program of research aimed at uncovering children's acquisition of script representation. They asked young children to describe events such as eating at home or eating at a day-care center, and derived a set of common elements mentioned by all the children. A common organization of these events was found, in terms of both the sequencing and the existence of a common core. Young children's organizations were very similar to the adult ones (Bower, Black, & Turner, 1979). What was acquired with learning (over a period of 3 months spent eating at a day-care center) was the addition of more basic events (Nelson, 1978), as well as the development of alternative paths leading from one element in the sequence to another element (Gruendel, 1980). The existence of a definitive script structure can also be tested by determining whether young children recognize deviations from a script (Wimmer, 1979). Basically, children ages 4 and 6 can recognize anomalies in a script, though Adams and Worden (1986) have shown that between the ages of 3 and 7, children's ability to detect script anomalies improves. These authors reasoned that a higher proportion of young children's scripts are comprised of atypical items, thus implying that their script boundaries are initially "fuzzy," but improve with experience.

In the study by Ceci *et al.* (1981), children as young as 7 years of age detected anomalies in an experimenter-prepared script involving familiar television personalities attempting to solve a crime. That children possess a "script" was evident: When the same dialogue was used with unfamiliar character names, children were not biased by their prior knowledge. Thus, few or no script-based intrusions were found in the unfamiliar condition.

A child's comprehension of stories can also be understood in terms of the script-like structure of the stories. We do not review this work here, since most of it has already been elegantly described in a chapter by Mandler (1983). These findings on script knowledge mirror those discussed concerning children's categorical knowledge (Section V,B).

To summarize, this section presented issues that are of current concern, namely, what is the structure of children's knowledge and how is it different from adults' knowledge structure. We began by attempting to clarify what we mean by "structure" in comparison to other terms that are often used, such as content, mode, and format of a representation. Several kinds of representational formats (dimensions, clusters, categories, networks, and scripts) were then discussed, particularly in the context of relevant developmental findings.

VI. What Is Structural Change or Restructuring in Memory Development?

An important issue that concerns many developmental psychologists is whether structures change with development. This has been an extremely difficult question to answer, in part because of a lack of consensus on precisely what *structure* means. The questions are obvious. What are the differences (if any) between structural change and representational change? What are the transitional mechanisms responsible for the change? And are these changes radical and abrupt? The answers to these questions (as we have alluded to in Section V) are contingent upon having (1) a way to represent knowledge, (2) a way to quantify the changes, and (3) a way to determine whether the changes are radical or not.

Changes in structure often refer to the availability of new information, which allows the child to represent a new concept (or represent an old concept in a new way) or solve a more difficult problem that he or she could not have solved before. This is basically the notion introduced by Piaget (1971), Fischer (1980), and Halford (1984). We are in basic agreement with this concept. That is, both children and adults undoubtedly cannot understand and represent a concept when the corresponding structure for that concept does not exist in memory. Gentner's work provides an example. Young children's representation of the verb *buy* lacks the component of transfer of money. Consequently, although they may use the term *buy,* they cannot understand it in the same way that older children do. Similarly, Clark and Garnica's (1974) demonstration of the acquisition of "marked" features suggests that young children confuse deictic verbs (e.g., *come* versus *go*) because their concepts lack certain components (in this case the speaker's spatial–temporal reference point).

In interpreting the examples just cited, we assumed that one aspect of structural change involves the addition of new components, which is a quantitative change. An assumption in Piagetian and neo-Piagetian theories is that developmental changes in structure are accompanied by the acquisition of new and more sophisticated structures. Keil (1981) referred to such changes as "radical restructuring." Hence, the critical issues in development are what constitutes a radical restructuring, and how such changes come about (that is, what are the transition mechanisms, if radical restructuring does occur).

We need to consider first how structural change can be described and to distinguish between changes in the structure within a mode of representation and changes in the structure that require a change in the mode. For example, a prominent issue in developmental theories concerns the potential for change in the young child's mode of representation from primarily image-based to proposition-based. Such changes, if they take place, would certainly be considered a radical restructuring in representation. However, we are in agreement with Kosslyn's (1978) hypothesis that such changes probably occur gradually, reflecting a change from a reliance on an imagery-based representation to a reliance on one that is propositionally based, after the child has encountered numerous instances of an event or object, rather than with the view that one mode is available at a certain age and another mode is available at a later age.

The discussion that follows is focused on the possible changes in structure that are within the same mode and format. That is, given that a child's knowledge at a given age can be represented by a given mode and format, what kind of changes can be considered a radical restructuring? Keil (1981) has proposed a few possibilities. We can begin by examining his taxonomy.

One view, derived basically from Rozin's (1976) idea of "greater access," is that the entire knowledge structure is always present. Development or restructuring is the ability to access a wider range of the structure and eventually the entire structure. Keil has depicted this in Sequence A in Fig. 2. Let us capture development by referring to it as three levels. At Level 1, the child can access one area of the structure with Task A and another area with Task B as indicated by the circles. They do not overlap. At Level 2, the child can access some overlapping knowledge, and at Level 3 the entire knowledge base can be accessed with any

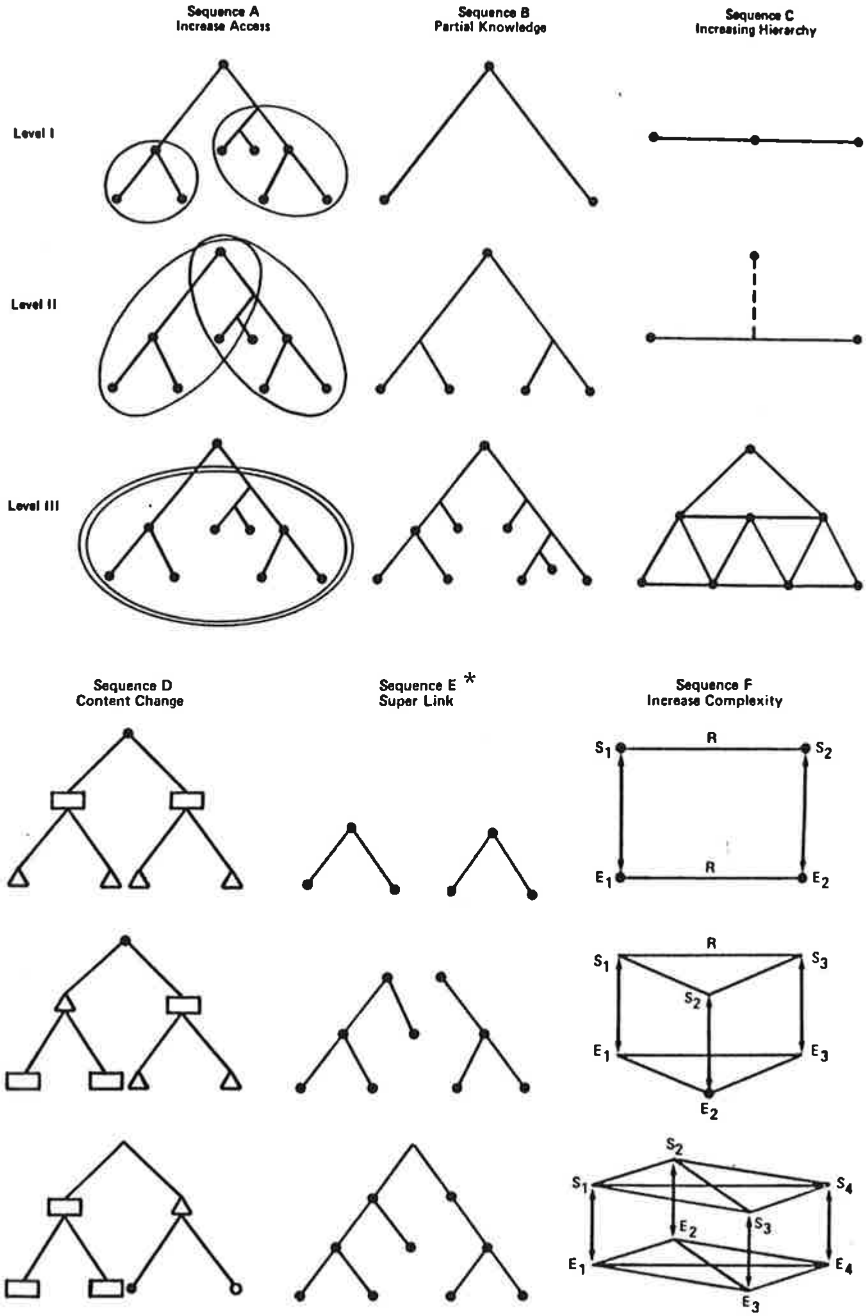

Fig. 2. Developmental sequences representing structural changes (adapted from Keil, 1981; Halford, 1984).

*Corrected from published version

task. Some of our current work can be interpreted to support this idea. For example, some very young children (age 4–6) respond in an animistic way when probed with Piaget-type questions such as ''Is the wind alive?'' The child's confirmation response draws upon the notion of movement as an indication of living. However, the same child, when probed with other types of questions such as ''Can you run with a doll?'' (Gelman, Spelke, & Meck, 1983), will deny the possibility of such activities, yet confirm that you can run with a dog (Chi, 1986). One interpretation of this data is that each of the questions probe only one area of the knowledge structure, thus only the wind, dogs, or dolls node is accessed with each question. So, for example, when the wind-alive question is asked, the concept ''alive'' is accessed and movement happens to be a salient attribute of the ''alive'' concept. This also explains why the child does not view his responses as conflicting, since the different probes do not access overlapping structures.

Keil's theory, shown in Sequence B in Fig. 2, seems to be primarily one involving a quantitative increase in the knowledge base, where the structure changes only to the extent that it becomes more complete and differentiated. Again, many sets of data can be interpreted this way. Keil's own data, in particular, show that the constraints are basically there to guide the order in which children acquire concepts. One could also interpret Nelson's (1978) data on the acquisition of additional elemental events for a child's script (discussed in Section V,D) as fitting this model.

Sequence C is another candidate for possible change. That is, knowledge can be organized initially in a more linear or latticelike way and eventually become more hierarchic with age. The clustering-type of studies basically tend to reveal this kind of change. (See the discussion of Storm's data, 1980, and also Corsale & Ornstein, 1980.) Research on expert and novice children's goal structures for knowledge of *Star Wars* has also yielded evidence compatible with Sequence C. Basically, as children's knowledge increases, their goal structures begin to develop from a linear mode to a hierarchical mode. In the intermediate stage, the two extreme levels of goals are present, and during the last stage, the intermediate-level goals are filled in (Means & Voss, 1986). One can conceive of development as making the same progression. Finally, the common results showing young children's inability to do class inclusion and derive inferences from hierarchy would also be consistent with such a format. Such changes from a linear to a hierarchical representation are a form of restructuring.

In Sequence D we are assuming that both children and adults have a hierarchical structure, but the contents of the nodes are different. With development and learning, the critical features for the adult become salient for the child as well. Many kinds of evidence show that adults and children consider different features to be critical. For example, in many of the studies cited in this article, we have seen that children consider perceptual features more important or discriminating than conceptual distinctions. In studies of children's concept of living, young children clearly consider movement to be a very salient attribute but adults and older children do not. In a very innovative study by Carey (1985), an explicit change in children's choice of critical features was demonstrated. She showed that younger children (ages 4–7) judge whether an animal has a biological property (''Does a shark breathe?'') on the basis of how similar the animal is to people. The more similar the animal is to people, the more likely young children are to agree that the animal possesses those biological properties that they know people have. That people are the best exemplar of their concept of living can also be seen by the pattern of attribution of properties to different animals. For example, if young children are told that people have spleens, they are likely to attribute that property to other animals. Older children, who have a more complete knowledge of biology, have a similar attribution pattern whether the property is taught of dogs or people. Clearly, then, this study showed that children's concept of the important properties of *living* changes as they acquire more biological knowledge.

Although many of these studies were not conducted to address the notion of hierarchy per se, the point remains that both children and adults could have a hierarchical representation of concepts, but with different contents for the nodes. Another example showing that young children do possess hierarchical representation is seen in a child's sorting of classmates' names (Chi, 1985). The child, who was 5 years old, represented classmates hierarchically, although the top-level nodes consisted of the seating sections, rather than *gender* as one might expect from adults. This was shown by the pauses in the child's output while generating and/or recalling the names. Long pauses occurred at boundaries of seating sections, whereas short pauses segregated the names of children seated within the same section. Hence, development may be viewed not as the acquisition of content knowledge, nor as the addition of partial knowledge to complete a hierarchy, but as the reorganization of the existing knowledge so that the more salient, abstract, or important attributes are stored at higher levels of the hierarchy. This kind of change can also be considered a reorganization of knowledge.

We propose that Sequence E seems the most plausible in terms of capturing developmental differences as well as representing restructuring. We assume that children acquire separate modules of knowledge that are coherent in and of themselves—that is, they have ''local coherence.'' At some point, the child acquires linkages among the localized modules. The acquisition of these ''super links'' between the modules allows the child to ''see'' or ''understand'' the entire structure and to generate performance competence that seems to have resulted from radical restructuring. But as can be seen, again, one need not consider this kind of change as radical restructuring, because the mechanism that produces a link between two coherent localized modules need not be any different from the mechanism that produces a link within a local module. However, the resulting performances may be qualitatively different before and after the acquisition of the super links.

Again, our data on animistic thinking can be interpreted this way. The child has a coherent knowledge of what *alive* means, in terms of the salient attribute of movement. The child also has coherent knowledge about separate objects such as dogs and dolls. However, the link between the ''aliveness'' of dogs, dolls, and living nodes may not be well defined or connected. Hence, the child appears to have misconceptions in the sense of having contradictory knowledge, but in reality the knowledge is not connected and so is not contradictory to the child.

Another finding that can be interpreted to be consistent with this view is that young children can sort on the basic level but not at the superordinate level (Gelman, 1978). (See also discussion in Section V,B.) One could say that the young child has developed coherent knowledge structures for basic-level objects, but has not developed the super link to connect these basic objects.

Yet another example can be interpreted in the same way. Lawler (1981) noted that his daughter knew how to do mental calculation with money. At the same time, she also knew how to do mental arithmetic involving pure numbers by breaking them into multiples of ten and counting up the remainders. She did not, however, connect the two techniques. For example, when asked to add 75 and 26 in terms of money, she could do so by saying ''that's three quarters, four, and a penny, a dollar one'' (p. 4), but when she was adding them as numbers, she did it by adding tens and counting the remainders, such as ''seventy, ninety, ninety-six, ninety-seven, ninety-eight'' (p. 4). Lawler (1981) referred to these separate skills as microworlds. Although they both required the same skill in arriving at the sum by counting the leftover units, the two microworlds had distinct conditions for their activation. Only later did Lawler observe moments of insight when his daughter first noticed that she could combine her tens microworld with her money microworld. Chi and Rees (1983) interpreted these data as supporting the notion of access. That is, even though the two subskills might seem to an adult to be part of the same general skill, to a child they are actually separate. Access to the money microworld is limited to situations where money is explicitly mentioned, and access to numerical addition is accomplished when actual numbers are presented.

It is difficult to determine which of the five sequences just described qualifies for radical restructuring. Perhaps the problem lies in the omission of theories that truly propose to reflect restructuring. Sequence F, shown in Fig. 2, is one proposed by Halford (1984). The different structures at each stage are supposed to reflect a different mode of thought, one that is more complex and increases in dimensions. One interpretation of how Sequence F differs from Sequences A–E is that a different mode of representation may be needed to represent each stage. This is a very tenuous conclusion.

The point remains, however, that it is fairly straightforward to compare and contrast Sequences A–E because one can discuss them all within the same form of representation. But it is difficult to determine which of the changes depicted in Sequences A–E can be considered radical restructuring. There are two ways. One method is to develop a metric to quantify a structure and postulate that a structure has undergone radical changes when a certain criterion is reached. Another method is to judge whether the performance outcome corresponding to one level of the knowledge structure can be considered qualitatively different from the preceding level. The question of restructuring and qualitative change is still an open one.

VII. The Role of Other Types of Knowledge in Memory Development: A Caveat

We conclude this paper with an admission of our omissions. Our principal aim in writing this paper was to provide a knowledge-based framework that could be useful in interpreting much of the memory development literature of the 1970s and 1980s. Because of the nature of the studies we reviewed, the resulting framework was largely composed of a scaffolding of content knowledge of various types. We argued that most of the age differences that were observed in previous studies could be explained in terms of the ways in which content knowledge developed (i.e., was acquired and structured). Thus, we have focused on a reanalysis of these studies almost exclusively in the context of age-related differences in content knowledge.

A danger in this approach is that it may create the impression that changes in content knowledge are the sole source of knowledge-based developmental differences in memory. Many other types of knowledge also change: planning knowledge, ''meta''knowledge, and procedural skills. We neglected these types of knowledge changes either because they have been emphasized in other writings (as in the case of metaknowledge) or else we know very little about them (such as the development of planning and procedural knowledge). In fact, the most promising way to proceed in the study of cognitive and memory development is to examine how content knowledge interacts with the development of planning, metaknowledge, and procedural knowledge. Many studies cited in this paper were aimed at this goal, although we did not focus upon it. The cited studies of sorting and classification, for example, were attempts to tease apart the contribution of content knowledge and an operational skill in Piaget's sense (such as classification). Nevertheless, numerous recent studies address this interaction issue more explicitly, such as the relationship between (1) content knowledge and strategic usage such as rehearsal (Ornstein & Naus, 1984), (2) the availability of numerical schemata and operations (Siegler, 1981), (3) the hierarchical structure of knowledge and classification (Chi, 1985), (4) knowledge and comprehension (see Schmidt & Paris, 1983, for an excellent review), and (5) content knowledge and the kind of reasoning and inferences that children use (Ceci *et al,* 1980, Gobbo and Chi, 1986.

One reason for the slanted focus of this article is that since the mid-1960s, memory development has been seen as largely the development of strategic and meta knowledge. Hence, the imbalance created here is intentional to see to what extent we can apply the "structure of content knowledge" explanation to the extant literature. This intentional imbalance also explains the selectivity of the literature reviewed. The omission of studies aimed at relating content knowledge to other types of knowledge is logical; that is, unless we convince the readers first that content knowledge is important, we cannot begin to stress the role of its interaction with other knowledge.

Finally, we encourage our colleagues to examine the extent to which individual differences in memory and cognition exist at a given level of content knowledge. To date, there is no scientifically adequate answer to the question, "How much of memory performance is attributable to content knowledge?" We have argued that some relationship surely must exist, but the strength of the relationship awaits further research. Until then, it would seem prudent to remain skeptical about alleged developments in memory and cognition that emanate from studies where differences in content knowledge are a more parsimonious explanation.

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