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# Relationships among processing speed, working memory, and fluid intelligence in children

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**Abstract**

The present review focuses on three issues, (a) the time course of developmental increases in cognitive abilities; (b) the impact of age on individual differences in these abilities, and (c) the mechanisms by which developmental increases in different aspects of cognition affect each other. We conclude from our review of the literature that the development of processing speed, working memory, and fluid intelligence, all follow a similar time course, suggesting that all three abilities develop in concert. Furthermore, the strength of the correlation between speed and intelligence does not appear to change with age, and most of the effect of the age-related increase in speed on intelligence appears to be mediated through the effect of speed on working memory. Finally, most of the effect of the age-related improvement in working memory on intelligence is itself attributable to the effect of the increase in speed on working memory, providing evidence of a cognitive developmental cascade. © 2000 Elsevier Science B.V. All rights reserved.

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Developmental research has shown that as children mature, their information processing becomes faster (Hale, 1990; Kail, 1991a,b), their short-term memory capacity increases (Dempster, 1981), and, of course, their ability to reason improves (Wechsler, 1981; Court and Raven, 1982). The goal of the present review is to consider how these changes in children's processing speed, working memory, and intelligence are related.

With respect to individual differences among young adults, it is well established that processing speed and intelligence test scores are correlated, although the

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strength of this relationship is still a matter of debate (Neisser et al., 1996). It has recently been suggested that individual differences in short-term or working memory underlie the correlation between speed and intelligence (Jensen, 1993). That is, the ability to reason and solve problems requires the use of information held in working memory, and this information is subject to loss (due to either decay or interference). As a consequence, faster processing is more likely to permit reasoning to reach completion before the requisite information is lost (Jensen 1993; Miller and Vernon, 1996). Just and Carpenter (1992) have further suggested that, because the amount of information held in memory limits the ability to reason, larger working memory capacity should also be associated with better reasoning. Finally, it is possible that speed itself is related to working memory capacity because faster rehearsal allows one to maintain a larger amount of information in memory (Baddeley, 1981, 1986). To the extent that these hypotheses regarding processing speed, working memory function, and intelligence are correct, one would expect to find strong correlations between all the three of these variables, and recent research using adult samples reveals just this pattern (Kyllonen and Christal, 1990).

From a developmental perspective, it is important to determine whether the relationships between the variables hypothesized to underlie individual differences among peers in the ability to reason, also underlie age-related improvements in the ability to reason. Thus, two related questions arise, (a) does the age-related growth in working memory capacity result from age-related improvements in processing speed? (b) Do these speed and memory differences, together or separately, lead to the improvements observed in reasoning and problem solving during childhood? In order to address these questions, we will review the existing developmental literature on these three cognitive variables individually, as well as those studies that examined them in combination (i.e. speed and intelligence, speed and working memory, working memory and intelligence, or speed, working memory, and intelligence). Prior to this literature review, we will provide a brief set of definitions.

## 1. Definitions

### *1.1. Processing speed*

For many years, researchers interested in examining the relationship between the speed of information processing and intelligence used very simple tasks (e.g. simple reaction time or choice reaction time) to measure the processing speed. The reason for using simple tasks was to minimize the contribution of higher cognitive function that would be included in one's assessment of intelligence. Instead, the speed of information processing was meant to capture the speed at which an individual completed basic cognitive functions such as item identification or simple discriminations. Within this framework, some researchers even attempted to distill the cognitive speed from any motor speed involved in the actual execution of the response (this topic will be discussed in greater detail in a later section).

More recent findings from multitask experiments suggest that speed of information processing should be viewed as a general or task-independent construct. The speed of information processing of young adults has been found to be highly correlated across different tasks that span a wide range of complexity (Vernon, 1983; Hale and Jansen, 1994), and the speeded performance on many different tasks improve in concert during childhood, reflecting a global developmental trend in processing speed (Hale, 1990; Hale et al., 1993; Kail, 1991a, 1992a; Kail and Park, 1992; Kail, 1993). Some of the studies that will be discussed in the following sections measured processing speed by assessing performance on several speeded tasks and then derived a general speed index, but others measured the processing speed using a single task or an index derived from performance on a single task. Although, it is clearly preferable to use more than one measure for a construct, we will assume (as the authors did) that all the reviewed studies used measures that tap an underlying general speed construct.

### *1.2. Working memory*

This paper follows Baddeley's use of the term *working memory* to denote a memory system that expands on the more traditional concept of short-term memory (Baddeley, 1986, 1992). Within the working memory framework posited by Baddeley, a central executive system controls the functioning of (or allocation of attentional resources to) two hypothesized slave subsystems; one involved in processing verbal information and one involved in processing visuospatial information.

The *phonological loop* can be described as being analogous to a single, continuous loop of audiotape that records verbally encoded information. Presumably, information that is recorded onto the tape loop is lost through decay (or interference from new information) unless it is rehearsed or transferred to long-term memory storage. Brief retention of any information that undergoes verbal encoding, regardless of the modality of presentation (e.g. auditory presentation of words, visual or haptic presentation of nameable objects), is presumed to utilize the phonological loop.

The function of the *visuospatial sketchpad* is assumed to be similar to that of the phonological loop except that it involves information that is nonverbal. Thus, information that is obtained about the form of an object or the location of an object in space is encoded and stored by utilizing the visuospatial sketchpad. For the current purposes, the visuospatial sketchpad may be viewed as functioning in a fashion that is analogous to a single, continuous loop of videotape where visual information (i.e. nonphonological information) is recorded. As with the phonological loop, information may be lost through decay or through interference arising from the processing of incoming information.

Evidence supports the idea that there is a dissociation of working memory functioning for information that is verbal versus visuospatial in nature (Logie et al., 1994; Hale et al., 1996; Shah and Miyake, 1996), and there may be an additional domain for numerically processed information as well (e.g. Leather and Henry, 1994). Such evidence for multiple subsystems is not counter to Baddeley's conceptualization. Rather, Baddeley viewed his theory as a framework onto which other slave systems and domains could be added. Thus, in this context, working memory refers to a system with multiple subsystems, each of which is specialized for processing and maintaining information from different domains, and each of which is limited by the decay of information and the efficiency of processing information within the subsystem.

### *1.3. Intelligence*

Intelligence, as measured by a test like the Raven's Progressive Matrices, is conceptualized as a very general ability, often termed *fluid ability* or *fluid intelligence* (e.g. Snow et al., 1984; Carpenter et al., 1990), that is distinguishable from acquired knowledge, or *crystallized intelligence* (Horn and Cattell, 1967). In the current context, fluid intelligence is meant to be synonymous with reasoning ability. As such, it is not a static property of human functioning. Rather, fluid intelligence can be affected by a number of maturational and experiential forces. For example, an individual may undergo brain maturation during childhood or brain injury at any point in life and these processes or events may result in improvements or decrements in this general ability (Horn, 1976, 1982, 1985; Horn and Hofer, 1992).

*Intelligent quotient* (generally used as the term *IQ*) is a theoretically based construct that for children is calculated using age-adjusted scores. That is, IQ norms for children are determined separately for each age level such that an IQ of 100 corresponds to average intelligence in a child *relative* to his or her own age group. Thus, an IQ score 'corrects' for the fact that general intellectual abilities improve during childhood and yet does so in a manner that potentially maintains the rank order of individuals so that, from year to year, relative ability is largely maintained (Court and Raven, 1982). It is as a measure of developing intellectual ability that IQ is particularly problematic for the current purposes.

Use of this measure to discern patterns of intellectual growth or the developmental relationship between different aspects of cognitive function is not feasible because the use of age norms deliberately removes any developmental differences. In the present context, therefore, fluid intelligence is defined as the ability represented by the *raw score* obtained from IQ tests rather than the more commonly reported IQ score. We will use the term fluid intelligence and avoid the term IQ except when necessary to highlight methodological problems in specific studies.

## 2. Review of empirical literature

There is an extensive literature on processing speed, working memory, and intelligence in children. In the following review, we will begin by considering the relationships between age and speed, age and working memory, and age and intelligence separately. We will then turn to the relationships among these various cognitive measures as examined first in studies involving a single age group and then as examined in studies involving multiple age groups. Finally, we will consider the only two extant studies that address the relationships among age and all three cognitive variables.

Some of these topics have been the subject of a relatively small number of studies whereas some others have been recently reviewed. In contrast, the relationships among age, speed, and intelligence have been the subject of numerous studies, but this topic has not been recently reviewed. Therefore, this literature will be discussed in relatively greater detail in our review.

## 3. Age and speed

As children grow older, they are able to process information more quickly (e.g. Hale, 1990; Kail, 1991a,b, 1993). The nature of this developmental trend was clearly revealed in a study by Hale (1990) who tested four age groups (10, 12, 15, and 19 year olds) on a battery of four different processing speed tasks. Her results showed that the increase in speed with age was not specific to any one task but rather appeared to be global in nature. That is, across all tasks, the time required by children of a particular age group was approximately proportional to the time required by the young adult group (e.g. in all conditions, 12-year-olds were approximately 50% slower than young adults). Hale suggested that the systematic decrease in this proportion with age provided evidence for a *global developmental trend* in processing speed.

Kail (Kail, 1991a) tested the *global development trend* hypothesis by conducting a meta-analysis of developmental studies. He reanalyzed data from 72 studies that compared the reaction times (RTs) of groups of children aged 4 years and older to those of young adults on a wide variety of information processing tasks. The results of his meta-analysis showed that, consistent with the findings of Hale (Hale, 1990), at any given age the RTs of children were proportional to those of young adults performing the same tasks. In addition, he reported that the developmental improvement in processing speed (i.e. the age-related decrease in the degree of proportional slowing) was well described by an exponential (nonlinear) function. This function captures the fact that processing speed shows initially rapid and then progressively more gradual improvements throughout childhood and into adolescence. It is not until the middle of adolescence that adult levels of speeded performance are achieved.

Cerella and Hale (1994) recently conducted a literature review that included further analyses designed to assess the usefulness of exponential functions in describing age-related changes in speed across the life span. They showed that one exponential function can be used to describe age-related change during childhood and another to describe change during adulthood (see Fig. 1). When the two functions are combined, they form a single U-shaped function describing the gradual improvement in speed during childhood followed first by a plateau and then by an even more gradual decline during adulthood.

Taken together, these lines of research reveal that it is possible to accurately predict the speeded performance of groups across a broad range of ages (i.e. from

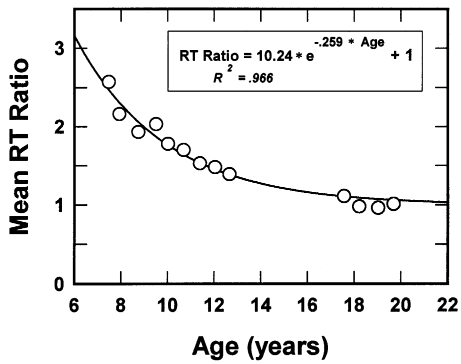


Fig. 1. Mean response time (RT) ratio plotted as a function of age. The open circles represent the means calculated for 13 groups created by subdividing the sample on the basis of age into bins of 8 months each. The solid line is the best-fitting exponential decay function (Equation 6 in Kail, 1991a). Reprinted with permission from Fry and Hale (1996).

age 6 to 80) relative to a young adult group. As will be discussed in subsequent sections, the pattern of nonlinear change with age observed for the development of processing speed is a recurrent pattern observed in other areas of cognitive development as well.

## 4. Age and working memory

In his 1981 meta-analysis of the development of memory span, Dempster pointed out that, although there are substantial individual differences in child and adult memory spans, the span of the average preschool-age child is approximately one-third that of the average young adult. Furthermore, he showed that most of the developmental improvement in memory span occurs during the early school years with span increasing by a little less than one item between 13 years of age and young adulthood. Thus, there is a definite nonlinear relationship between memory span and age (see Dempster, 1981, Figs. 1, 2, and 3) that parallels the nonlinear increase in processing speed over the same developmental period.

Gathercole and Baddeley (1993) recently reviewed the literature on the development of working memory, and they concluded that the increase in children's memory ability with age is based on increases in the efficiency of the working memory system. They pointed out, however, that although improvement in working memory appears to be purely quantitative beyond the age of 6 years, some evidence suggests that there may be qualitative changes in working memory function prior to entering the first grade. In particular, under some circumstances younger children prefer to use different mnemonic strategies than older children (Hitch and Halliday, 1983; Hitch et al., 1988).

For example, Hitch and Halliday (1983) showed that preschool-age children have a tendency to favor visual processing over phonological processing of visual information. This preference was revealed by testing 6-, 8-, and 10-year-old children on their recall of one-, two-, and three-syllable words, half of which were presented auditorily (e.g. the word ‘cat’, ‘monkey’ or ‘banana’), the other half of which were presented in the form of a picture (e.g. a picture of a cat, monkey, or a banana). Hitch and Halliday found that the 8- and 10-year-old children showed a word-length effect (i.e. recalled fewer long words than short) for names of objects that were presented pictorially and the names of objects presented aurally (i.e. words read aloud), whereas the 6-year-old children showed a word-length effect only for aural presentation of words. This finding suggests that, unlike older children and adults, 6-year-old children do not automatically translate pictorial information into their corresponding object names (at least when the goal is to memorize a list of items).

Gathercole and Baddeley (1993) suggested that very young children might not learn that phonological recoding of pictorially presented objects serves to enhance memory performance until they go to school and regularly need to use such skills. Similarly, they noted that the spontaneous use of active rehearsal does not appear in children until they are proficient readers (i.e. between the ages of 6 and 8 for most American and European children). Thus, the demands of school may encourage the development of these working memory skills.

Recent work by Cowan (Cowan 1992; Cowan et al., 1994) suggests other reasons why preschool children may perform more poorly on memory span measures than older children. Cowan obtained evidence that the relation between articulation rate and memory span breaks down in younger children (i.e. 4-year-olds who are faster with respect to their speech rates perform more poorly on memory span tasks). He suggested that this is because there are qualitative differences in what mnemonic strategies are used at different ages. Despite the identification of specific qualitative differences between working memory function in pre-school children and school-age children, however, researchers are unanimous in their conclusion that the improvements in working memory once children enter school appear to be purely quantitative in nature (Dempster, 1981, 1985, 1992; Gathercole and Baddeley, 1993). We will describe the two studies that underscore the nature of this quantitative change in working memory function during childhood, adolescence and into adulthood.

Whereas earlier reviews (Dempster, 1981; Gathercole and Baddeley, 1993) focused on age-related changes in standard measures of short-term memory, a more recent study by Siegel (1994) examined changes in working memory using tasks designed to place an online processing load on memory in addition to the traditional storage requirement. In addition, she tested her subjects on the ability to recall visually presented letters in the order in which they were presented. As may be seen in Fig. 2, her results from the letter span task provide a replication, in a single study, of the pattern of nonlinear growth in short-term memory ability suggested by Dempster’s meta-analysis.

Siegel’s (Siegel, 1994) unique contribution, however, was to address the question of whether the pattern of developmental change in short-term memory would hold for measurements of working memory performance under heavier processing

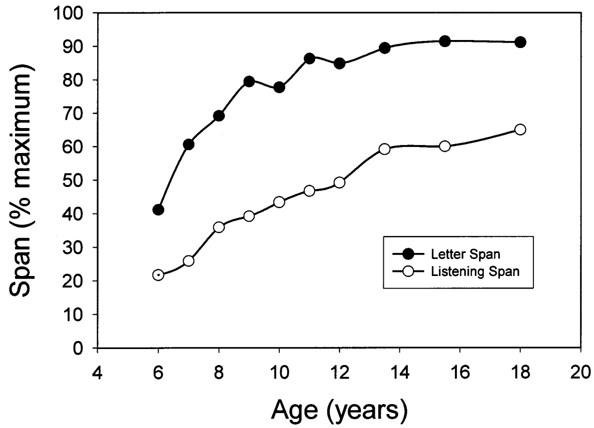


Fig. 2. Letter span (a measurement of storage of information) and listening span (a measurement of storage plus on-line information processing) plotted as a function age. Percent of the maximum attainable letter and listening spans were calculated for the data presented in Siegel (1994), Tables 1 and 2, respectively. Listening spans were obtained from a large group of individuals (over 1000) and letter spans were later obtained from approximately 75% of these individuals.

requirements. To answer this question, Siegel used a listening span task based on the one developed by Daneman and Carpenter (1980) to test the working memory of adults. Siegel's subjects heard sentences from which the final word was missing and were required to complete each sentence with the missing word. Following presentation of several such sentences, subjects tried to recall all of the missing words in order.

Siegel's (Siegel, 1994) data from the listening span task revealed a pattern of improvement similar to that observed in the letter span task. In particular, although the form of the growth curve is less nonlinear in the case of the listening span task, this may be due in part to a floor effect for the listening span task. Thus, Siegel's (Siegel, 1994) study not only supported Dempster's (Dempster, 1981) meta-analytic finding of a nonlinear relationship between age and standard memory span performance but suggested that a similar relationship extends to memory span performance under conditions in which additional processing requirements make demands on the working memory system above and beyond simple maintenance rehearsal.

## 5. Age and intelligence

Since the beginning of the century when Binet and Simon began developing the first test of children's intelligence, it has been known that as children grow older, their raw scores on intelligence tests improve. To illustrate the nature of the improvement in fluid intelligence, Fig. 3 plots raw Raven's Standard Progressive Matrices scores at the 25th, 50th, and 75th percentiles between the ages of 8 and 20 (data are taken from Table SPM IV, Raven et al., 1983). This figure clearly shows that age-related improvements in intelligent performance are nonlinear during the school years and early adulthood. As was the case for the development of both the information processing speed and working memory, the development of intelligence shows a rapid improvement in early childhood followed by a more gradual increase throughout adolescence.

Despite this well-known age-related improvement, it is interesting to note that there is no empirical literature that examines the development of fluid intelligence in children, per se. The research that is arguably the most relevant, however, is that on the development of analogical reasoning. Contrary to early ideas on this topic, analogical reasoning is not late-developing (for a review, see Goswami, 1991). Ample evidence now exists that by as early as age 3, children demonstrate analogical competence in solving both classical analogies (involving understanding the relationships among four terms: *a* is to *b* as *c* is to *d*) and in solving problem analogies (involving the use of analogical reasoning in order to solve a *target* problem after exposure to a *base* problem that has been solved earlier).

Performance on analogical reasoning tasks does improve with age (e.g. Gentner and Toupin, 1986), as does the ability to verbalize the relationships involved in specific analogies (e.g. Levinson and Carpenter, 1974). What underlies these improvements, however, remains poorly understood. Although, young children have difficulties using analogical reasoning in the absence of hints or surface similarities (e.g. Holyoak et al., 1984), the same turns out to be true for adults (e.g. Gick and Holyoak, 1983). Knowledge of the relationships involved appears to be a necessary

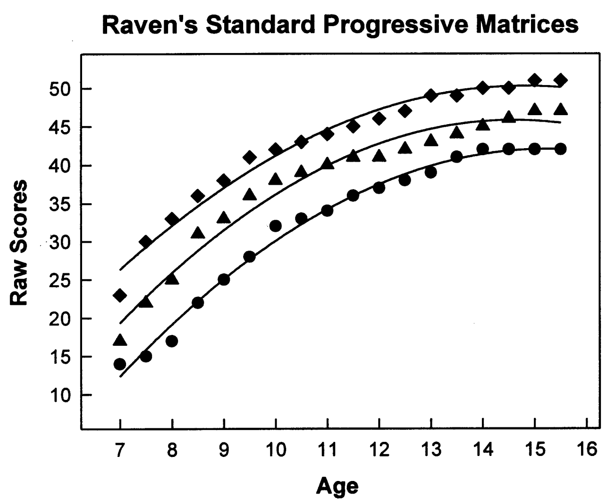


Fig. 3. Raw scores from smoothed summary norms (1979) for the standard progressive matrices plotted as a function of chronological age. Data are taken from Raven et al. (1983), Table SPM IV. Three percentiles are shown, 25th, 50th, and 75th, represented by circles, triangles, and diamonds, respectively. The solid lines represent the best-fitting second-order polynomial function fit to the data from each of the three percentiles separately.

condition for analogical reasoning to occur, and the knowledge base concerning specific relationships undoubtedly increases with age. Such knowledge is not a sufficient condition for analogical reasoning, however, and aside from increasing knowledge, it remains unclear what else develops with respect to analogical reasoning abilities.

It has been suggested that metacognitive skills (e.g. children's ability to reflect on their own knowledge, to explicitly seek out relational similarity, and to seek counter-examples) may play a role in the development of analogical abilities. There is currently not enough evidence, however, to evaluate the presence or absence of such skills in young children, and there is no evidence that better metacognitive abilities are associated with the performance of older children relative to that of younger children in analogy tasks (Goswami, 1991). Thus, although research on analogical reasoning would appear to be a potentially fruitful source of ideas on the causes of age-related improvements in fluid intelligence, the analogical literature provides no clear answers at the present time.

## 6. Age, speed, and intelligence

As mentioned, the developers of psychometric tests typically provide age norms for rescaling children's test scores (i.e. converting them to IQ scores) so as to correct for the nonlinear improvement in intelligence. For psychometricians, this scaling of intelligence serves two purposes; (a) it represents a prediction as to an individual's future level of intellectual performance under the assumption that intelligence is an enduring individual trait; and (b) it permits one to compare the performance of individuals of different ages because, regardless of the age of the individual, all IQ scores have been standardized to have the same mean and S.D. (e.g. 100 and 15, respectively).

Researchers interested in studying the relationship between individual differences in intelligence and individual differences in speed sometimes take advantage of the extensive IQ testing of children in schools and correlate children's IQ scores with speed measures. Given that the IQ scores are 'corrected' for developmental improvements in intelligence this approach would seem, at first blush, to be a reasonable one. However, unlike a partial correlation between speed and raw test scores with age statistically controlled, a correlation between speed and IQ scores corrects only for developmental changes in intelligence. In contrast, the partial correlation technique corrects for developmental improvements in both intelligence and processing speed.

When researchers fail to report the partial correlations that control for age differences in speed, readers may misinterpret their findings (e.g. Hemmelgarn and Kehle, 1984; Irwin, 1984; Jensen and Whang, 1994; Sacuzzo et al., 1994). These difficulties occur both with respect to understanding the relationship between individual differences in speed and intelligence and also with respect to understanding any possible developmental changes in the relationship between these variables. Issues concerning sample sizes, restriction of range, and the type and reliability of measures also contribute to the muddled picture of the effect of development on the relationship between speed and intelligence that emerges from the literature.

In what follows, we will refer to the confounding of maturational changes in speed with individual, ability-related differences in speed as the *chronological age/mental age confound* (CA/MA confound). This confound has the potential effect of inflating the correlation between speed and raw intelligence scores and attenuating the correlation between speed and IQ or other age-normed scores. These problems tend to increase with the range of ages tested.

Consider the data that are obtained when one tests children of different ages. These data obviously reflect *age-related differences* in speed and fluid intelligence as well as *individual differences* among peers in both speed and fluid intelligence. The combined effect of both kinds of differences increases the variance shared between speed and fluid intelligence over that in an age-homogeneous sample. Consequently, any correlation between speed and raw intelligence scores reflects this increased variance and, as a result, the obtained value of $r$ is likely to be inflated relative to the true value in an age-homogeneous sample. For example, very young children, even those who are bright for their age, will tend to be slower and have lower raw scores than much older children, regardless of their ability, and this will contribute to the correlation between speed and raw test scores. Moreover, any correlation between speed and age-normed scores is likely to be correspondingly attenuated by the effect of age differences in speed. For example, very young children who are bright for their age will have high age-normed scores but slow speeds thereby attenuating the correlation between speed and age-normed scores.

The CA/MA confound can be avoided by using raw scores and partialling out the effects of age on both speed and fluid intelligence, thereby making it possible to determine the combined and separable effects of age-related and individual differences in speed and fluid intelligence. Studies that focus on a single age group, obviously avoid the problem of the CA/MA confound. The drawback of such a study, of course, is that it is only in a position to answer questions concerning the relationship between speed and intelligence within the age group studied and can say little about development when considered separately. The majority of the research on fluid intelligence in children falls into this category of single age group studies. Unfortunately, most of the studies that have used multiple age groups have not taken the consequences of age-related changes in speed into account. Hence, as will become clear, such studies have done relatively little to elucidate the effect of age on the relationship between speed and fluid intelligence.

### *6.1. Studies of speed and intelligence in a single age group*

Most of the studies of the relationship between speed and fluid intelligence in school-age children have focused on groups of individuals who are all the same age or in the same grade at school. The results obtained from such studies have been comparable with those obtained from age-homogeneous groups of adults. Correlations have been found to vary widely, depending on the methods of measuring RT and intelligence, the reliabilities of these measures, and the population under study (i.e. whether samples included mentally handicapped individuals or not). These correlations are almost always negative because speed typically is measured in terms of time and more intelligent individuals tend to take less time to respond. The magnitude of the correlation appears to be related to the same types of methodological factors regardless of whether one is testing children or adults. Importantly, the strength of the relationship between individuals' speed and intelligence does not appear to change systematically during childhood.

This is a significant observation because it is contrary to what would be expected based on Brand's (Brand, 1981) theory of the development of intelligence. Brand argued that because children approach a physiological ceiling in speed as they grow older, there would be a decrease in speed variability (i.e. a restriction of range) and a resulting reduction in the possible correlation within an age group as they approach adulthood. To facilitate the evaluation of Brand's claim, we will consider the findings from single-age group studies in chronological order by the age of the children.

The youngest groups examined in age-homogeneous studies consisted of 6–7-year-old children (Hulme and Turnbull, 1983; Nettelbeck and Young, 1989, 1990). The three studies that examined this age-group, all used inspection time (IT) as the measure of speed and the Wechsler's intelligence scale for children-revised (WISC-R) as the measure of intelligence. IT is a measure of perceptual processing speed determined by estimating the briefest exposure time an individual needs to process new information accurately. To obtain such an estimate, individuals are typically required to make a discrimination between two lines (i.e. to say whether the lines are the same or different lengths) following a very brief exposure (e.g. 150 ms). The exposure duration is titrated up and down to find the shortest possible exposure duration or IT at which an individual is approximately 95% accurate at (Eysenck, 1986).

The WISC-R consists of a battery of 12 subtests, half of which provide a measure of performance IQ (PIQ) and half of which provide a measure of verbal IQ (VIQ). The six subtests whose scores contribute to PIQ are block design, object assembly, picture arrangement, picture completion, coding, and mazes. The six VIQ subtests consist of information, similarities, vocabulary, arithmetic, comprehension, and digit span. Scores on all 12 subtests are used to determine an individual's full-scale IQ (FSIQ). The PIQ versus VIQ distinction has sometimes been mapped onto the fluid/crystallized distinction (Eysenck, 1987). Because the WISC-R was not created specifically to test fluid and crystallized intelligence, this mapping may be less than ideal (e.g. digit span may be better categorized as a working memory task that is more closely related to fluid ability; Horn and Hofer, 1992). Despite this drawback, PIQ tends to correlate somewhat more highly with processing speed in young adults than do either VIQ or full-scale IQ (Eysenck, 1987), although it is not altogether clear whether this is because the performance measures tend to be speeded or because fluid intelligence is causally related to speed.

Nettelbeck and Young (1990) obtained a correlation of $-0.31$ in 6-year-old children using the PIQ subscales and in their 1-year follow-up of a subset of the same children obtained a correlation of $-0.28$. Hulme and Turnbull (1983) tested children 6 and 7 years of age and obtained a correlation of $-0.20$ using full-scale IQ — a value very similar to the correlations obtained by Nettelbeck and Young (1989).

There are no published studies that included only 8-year-old children. There are, however, five studies that have used only 9-year-old children (Chan et al., 1991; Lynn and Wilson, 1990; Lynn et al., 1990, 1991; Ja-Song and Lynn, 1992). All five studies used the same measure of intelligence, the Raven's Progressive Matrices. In addition, all the five studies used an apparatus for measuring RT developed by Jensen (1987) and often referred to as a Jensen apparatus.

Raven's Matrices is a figural reasoning test in which multiple novel geometric shapes are transformed in a rule-governed fashion. The task is to find the solution that best completes the pattern of transformed shapes from among a set of alternatives. The Raven's has been hailed as the best measure of fluid cognitive ability (Marshalek et al., 1983; Snow et al., 1984; Carpenter et al., 1990), and for this reason it has been frequently used in research on intelligence.

Processing speed measures obtained using a Jensen apparatus capitalize on the orderly relationship between the number of choice alternatives and the time it takes to make a choice. This relationship, often referred to as Hick's law, states that RT will increase linearly as a function of the base two logarithm of the number of alternatives (Hick, 1952 also see Eysenck, 1987; Jensen, 1987). The Jensen apparatus used to measure this relationship consists of a 'home button' and eight lights, each of which has a corresponding response button, and the number of choice alternatives is varied by changing the number of lights that are used.

For each block of trials, the participant is informed of the number and locations of the specific lights that may be illuminated. A participant must hold down the home button until one of the possible lights is presented. At this time, the participant must release the home button and press the button corresponding to the light. Thus, the RT may be decomposed into the time to make a decision (i.e. DT, time from the light presentation until the release of the home button) and the time to move from the home button to the response button (i.e. movement time or MT).

DT is commonly conceptualized as the central processing time, and MT is assumed to represent only the time required to make a peripheral motor response (e.g. Jensen, 1987). For Jensen (and for the researchers using his apparatus), DT is the only measure of real interest. Other researchers have also taken advantage of Hick's law but have not measured DT and MT separately. In either case, the amount of time a subject takes to respond is determined for each number of response alternatives in order to estimate the slope and intercept of the regression of these times on the logarithm of the number of alternatives. Then, the regression parameters for different subjects are correlated with measures of their fluid intelligence. Speed/intelligence correlations based on the RTs for different numbers of alternatives are also often reported. The importance of using the whole RT or only the DT portion of the RT has been hotly debated, but Eysenck (1987) pointed out that there is no discernible difference between the two measures in the magnitude of the correlations with intelligence test performance that are obtained.

Returning to the five studies using 9-year-old children, the only substantive variation between these studies was that they tested children of different national origins (including British, Irish, Korean, and Chinese). National origin, however, appears to have very little effect on the magnitude of the correlation obtained between speed and intelligence. The correlations typically were lowest with RTs for single- or two-choice alternatives and somewhat higher when RT reflected more choice alternatives or when intelligence was correlated with the slope based on all the RTs. In general, the correlations tended to be low to moderate. For example, Lynn and Wilson (1990) obtained correlations ranging from −0.03 to −0.19, whereas Lynn et al. (1990) obtained a somewhat higher range of correlations (−0.22 to −0.33). Thus, the correlations obtained from the 9-year-old children are generally consistent with those obtained from the 6- and 7-year-old children.

Somewhat higher correlations have been reported for 10- and 11-year-old children, but not with 12-year-olds, suggesting that the observed variations are not related to age. Specifically, Seymour and Moir (1980) tested 10-year-old children and obtained correlations ranging from −0.47 to −0.53 between performance on a short-term memory scanning task and scores on the Moray House Test of intelligence (a measure of verbal reasoning ability). Similar results were reported in two studies of 11-year-old children. Jenkinson (1983) tested children using the Raven's test and memory scanning, sentence-picture comparison, and picture identification tasks and reported correlations ranging from −0.28 to −0.43, depending on whether separate task RTs, memory scanning slope, or an averaged speed factor was used. Spiegel and Bryant (1978) tested children using the Lorge–Thorndike measure of nonverbal intelligence and a group of RT tasks including matrix solutions, sentence completions, and picture identification. In this case, depending on the task and the type of RT parameter calculated, correlations ranged from −0.57 to −0.60.

These robust correlations might lead one to conclude that there could be a tendency towards *stronger* correlations with increased age, rather than weaker as predicted by Brand (1981), but the results of three studies of 12-year-old children argue against such a conclusion. Smith and Stanley (1983) reported correlations ranging from 0.00 to −0.34 between RT measures obtained using a modified Hick paradigm and scores on the WAIS subtests and on the Cattell Culture Fair test of intelligence. Similarly, Carlson et al. (1983) reported a correlation of −0.13 between a fluid intelligence measured using the Raven's and general speed factor obtained from RTs on the Jensen apparatus, and Cohn et al. (1985) obtained correlations from −0.15 to −0.30 using similar procedures. The correlations reported in all the three of these studies of 12-year-olds are obviously lower than those reported in the studies of 11-year-olds but are quite similar to those reported in studies of younger children (i.e. 6–9-year-olds).

Finally, correlations between speed and intelligence also have been reported for early adolescents aged 13 and 14 years. All the three studies of this age group used the Raven's test to measure intelligence, but one (Deary, 1994) used IT as the measure of processing speed whereas the other two (Jensen and Munro, 1979; Carlson and Jensen, 1982) used the Jensen apparatus. Both the highest correlation

( − 0.54 reported by Carlson and Jensen for a 13-year-old sample) and the lowest correlation ( − 0.37 reported by Jensen and Munro for a 14-year-old sample) were obtained from the two studies that used the same procedures.

Thus, although the correlations obtained for the oldest child groups are moderately high, there is a pattern of rises and drops in the magnitude of the correlation between speed and intelligence across age such that the youngest (6–7-year-old) children do not have the lowest correlations and the oldest (13–14-year-old) children do not have the highest. Rather, the highest correlations are reported by studies of 10- or 11-year-olds whereas the lowest correlations are reported by studies of 9 and 12-year-olds, hardly evidence of a systematic developmental progression. Certainly, there is no pattern of decline in the strength of the relationship with age, contrary to Brand's (Brand, 1981) prediction. Moreover, it should be noted that the range of correlations between speed and intelligence in children is from 0 to − 0.60, very similar to that observed in studies using groups of age-homogeneous adults (Eysenck, 1987).

### *6.2. Studies of speed and intelligence in multiple age groups*

Eleven studies have examined the relationship between speed and intelligence in age-heterogeneous groups of school-age children. Unfortunately, most of these studies confounded the age-related differences in speed of processing with ability-related differences in the speed of processing. In the usual case, this confound may have attenuated the relationship between speed and intelligence and resulted in the reported low correlations, although in one case (i.e. Wilson and Nettelbeck, 1986), the confound resulted in the anomalous finding of a significant positive correlation. That is, they reported that high IQ individuals took longer to process information than low IQ individuals.

We will begin by describing this study as it provides a particularly telling example of the CA/MA confound. The peculiar results resulted in part from the fact that Wilson and Nettelbeck (1986) examined IQ in groups of children formed on the basis of mental age. An individual's mental age was calculated as the age for which the average raw score was the same as the individual's raw score. Thus, a child whose mental abilities were average for his or her age would have the same mental and chronological age. In contrast, a child of high cognitive ability would have a higher mental than chronological age, reflecting the fact that his or her abilities were more commensurate with those of an average older child.

Wilson and Nettelbeck (1986) categorized children as belonging to either a mental-age-8 group or a mental-age-10 group, making sure that there were children of high, average, and below average IQ within each mental age group. For example, Wilson and Nettelbeck's mental-age-8 group included high IQ children with an average chronological age of 5 years and low IQ children with an average chronological age of 10 years, and their mental-age-10 group included high IQ children with an average chronological age of 8 years and low IQ children with an average chronological age of 18 years. Thus, the high IQ children in each mental age group were always the youngest children and the low IQ children in each mental age group were always the oldest. In fact, in both the mental age groups the lowest IQ children were at least twice the age of the younger, high IQ children!

One can generally expect older children to be faster than younger children, and young children with very high IQs, although they may be fast relative to others of their own age, may still not be as fast as substantially older children who have low IQs and who may be slow relative to others of their own age. Thus, Wilson and Nettelbeck's (Wilson and Nettelbeck, 1986) apparently peculiar finding that within each mental-age group, low IQ children tended to be faster than high IQ children can be explained in the context of a maturational improvement in processing speed: *The low IQ children tended to be faster than the high IQ children because they were also considerably older*.

The Wilson and Nettelbeck (1986) study provides a very revealing, albeit extreme, example of how correlations can be affected by the CA/MA confound. In most of the other multiple age group studies, the CA/MA confound was not nearly as problematic. Nevertheless, none of the studies provides a clear picture as to the contribution of age-related changes in speed to the relationship between speed and fluid intelligence.

A study by Levine et al. (1987) is among the most informative. However, it exemplifies another obstacle to research on the developmental relationship between speed and intelligence. Specifically, it is often difficult to find a single test that is valid across the age range of interest if that range is fairly broad. Levine et al. (1987) tested 4th-, 7th- and 10th-grade children on a RT battery and on the Cognitive Abilities Test (a measure of nonverbal and verbal reasoning ability). Unfortunately, the researchers had to use different forms of the intelligence measure for the different age groups. As a result, they could only correlate speed and intelligence within groups and could not conduct any between-age-groups analyses of intelligence.

Nevertheless, viewed as a series of single studies each with a different age group, there was much less procedural variation in the procedures used by Levine et al. (1987) to test the different age groups in the study than existed between the studies of single age groups reviewed previously. Thus, the results of the Levine et al. (1987) study provide a useful check on our conclusions regarding the lack of a developmental trend. Consistent with the findings from the single-age-group studies, Levine et al. (1987) found no systematic change in the strength of the speed and intelligence relationship with age: Correlations ranged from $-0.05$ to $-0.32$ for the 4th-grade children, from $-0.16$ to $-0.41$ for the 7th-grade children, and from $-0.19$ to $-0.35$ for the 10th-grade children.

Four studies (i.e. Hemmelgarn and Kehle, 1984; Irwin, 1984; Jensen and Whang, 1994; Sacuzzo et al., 1994) tested several age groups on the same intelligence test but did not provide sufficient information to enable us to assess the relative influence of age-related differences and individual differences by comparing the correlation of speed and intelligence before and after controlling for age. Another study (Beh et al., 1994) focused on gifted children, and thus does not speak to the issues at hand.

Three age-heterogeneous studies (Anderson, 1986, 1988; Wilson et al., 1992) did report most, if not all, of the correlations necessary to estimate the separate contributions of individual and age differences to the relationship between speed and intelligence. Even in these cases, however, some problems remain.

The first study we shall consider is that by Wilson et al. (1992). A major goal of this study was the evaluation of Brand's (Brand, 1981) developmental theory of speed and intelligence and, in particular, the theory's prediction of a decrease in speed and intelligence correlations with age. To this end, Wilson et al. (1992) tested children ranging in age from 5.7 to 12 years of age. All the children were tested on the short form of the WISC-R and were given a *z* score based on their performance relative to the whole sample. Speed was measured as IT, and correlations between speed and age, speed and raw intelligence, and age and raw intelligence were reported (−0.15, −0.46, and 0.64, respectively). From these values, we were able to determine the partial correlations holding age and then speed constant. The correlations between speed and intelligence did not change when age was controlled. Moreover, the correlation between age and intelligence did not change when speed was controlled.

On the basis of the Wilson et al. (1992) study, one might be inclined to conclude that the contributions of age to the relationship between speed and intelligence is negligible. Indeed, the weak correlation reported for age and IT (−0.15) by these authors might be taken as evidence that age has very little effect on processing speed. It is important to note, however, that such a weak relationship between age and IT is inconsistent with the developmental literature on RT and with the developmental literature on IT.

Exactly what led to such an unusually low correlation between speed and age in these particular studies is not readily apparent, although given that developmental growth curves for IT latencies are, like their RT counterparts, negatively accelerated (e.g. Nettelbeck, 1987), it is possible that the strength of the relationship between age and speed may have been underestimated due to this curvilinearity. With respect to possible age differences in the strength of the relationship between speed and intelligence, Wilson et al. (1992) reported that their results failed to support Brand's theory. That is, the speed and intelligence correlations in the younger children were not consistently higher than the correlations in the older children, providing further evidence against Brand's (Brand, 1981) developmental theory.

The final two age-heterogeneous studies to be reviewed were both conducted by Anderson (Anderson, 1986, 1988). Anderson (1988) obtained IT measurements from groups of 8- and 12-year-old children who had earlier been tested on Raven's Progressive Matrices. Similar to the Wilson et al. (1992) study, the correlations between age and IT measurements were very weak or nonexistent (−0.29 and −0.15). Before considering this finding as further support for Wilson et al. (1992), it must be noted that the correlation between speed and intelligence was also very weak or nonexistent (−0.22 and −0.14). Thus, Anderson (1988) provides us with two anomalous findings.

Anderson (1986) provides a more consistent set of findings from three separate assessments of a group of 6-, 8- and 10-year-old children for whom he obtained raw scores and performance IQs from the WISC-R, as well as two measures of IT. He reported significant correlations between age and speed ( − 0.41), age and raw score intelligence (0.82), and speed and raw score intelligence ( − 0.52). Like Wilson et al. (1992) and consistent with our conclusions from age-homogenous studies, he found no systematic change with age in the strength of the relationship between individual differences in speed and intelligence (for example, correlations were strongest for the 8-year-old group in the first assessment but weakest for the 8-year-old group in the third assessment). Unlike Wilson et al. (1992), however, Anderson did obtain a moderate relationship between age and speed. With age statistically controlled, the correlation between speed and raw score intelligence dropped to − 0.35. This value is consistent with the correlations obtained from the age-homogeneous studies reviewed earlier. The difference between the full and partial correlations suggests that a substantial portion of the total speed and intelligence relationship in Anderson's sample can be attributed to age-related differences in speed.

Anderson (1986) also noted that when the effect of speed was statistically controlled, the correlation between age and raw score on the WISC-R dropped only slightly, from 0.82 to 0.78. Thus, despite the moderately strong relationship between age and speed, Anderson's (Anderson, 1986) data suggests that relatively little of the total age-related variance in raw score intelligence is mediated by speed.

How should we interpret the findings from Anderson (1986) and Wilson et al. (1992)? One possible explanation for the findings of weaker correlations between age and speed than might have been expected in Anderson's studies and Wilson et al.'s study, was suggested by Anderson (1988): "The RT variables relate to aspects of cognitive ability in development that change with age, whereas IT relates to those aspects that are relatively unchanging (with age)". We would offer an alternative explanation for the weak correlations between IT and age in both Anderson's studies and Wilson et al.'s (1994) study. Anderson (1986) reports a test-retest reliability for his IT measurements of 0.45. In contrast, the test-retest reliability of the processing speed measure obtained in our lab using multiple RT tasks is greater than 0.90 for both children and adults. Although, Anderson's suggestion regarding the difference between RT and IT remains intriguing, future studies need to include reliability estimates of speed and working memory assessments (estimates for IQ tests abound and one need only be careful to select well-established instruments) so that measurement issues do not cloud our theoretical interpretations of the data.

## 7. Age, speed, and working memory

The degree to which age-related improvements in speed and working memory are related has been the focus of research by Hulme and his colleagues (Hulme et al., 1984; Hulme and Tordoff, 1989; Roodenrys et al., 1993; Cowan et al. 1994), by Kail and his colleagues (Kail, 1992b; Kail and Park, 1994), and, most recently, by

Chuah and Maybery (1999). In general, age-related improvements in these research teams have shown that age-related increases in verbal memory span can be predicted from articulation rate (e.g. Hulme et al., 1984) and that articulation rate is determined by both age and individual differences in the processing speed (e.g. Kail, 1992b).

For example, Hulme et al. (1984) assessed the memory spans and articulation rates of four age groups (i.e. 4-, 7-, and 10-year-old children and a group of young adults). Both memory span and articulation rate were measured using items from the same pool of one-, two-, and three-syllable words, and both articulation rate (words per minute) and span were determined for each individual at each word length. Not unexpectedly, memory spans and articulation rates for each age group decreased with the number of syllables, and both spans and articulation rates for any particular class of items (e.g. one-syllable words) increased with age. The more important finding came from regression analysis results suggesting that the developmental increases in memory span may be attributable to the articulation rate increases.

More specifically, regression analysis revealed that a single linear function was sufficient to describe the relationship between the memory span and speech rate across all the age groups regardless of the word length. This finding reflects the fact that when two groups had similar articulation rates for particular classes of items, their memory spans for these items was also very similar. For example, very similar rates were recorded for 4-year-old children articulating one-syllable words, 10-year-old children articulating two-syllable words, and young adults articulating three-syllable words, and correspondingly, the memory spans of 4-year-olds for one-syllable words, of 10-year-olds for two-syllable words, and young adults for three-syllable words were also very similar.

The underlying assumption of these studies, and of Kail's recent research on this topic, is that articulation rate is not primarily a measure of motor ability, but that it reflects the rate at which items can be covertly rehearsed. It is this covert rehearsal speed that is assumed to determine memory span. Following up on this idea, recent studies by Kail (Kail, 1992b; Kail and Park, 1994) have examined the extent to which developmental increases in articulation rate simply reflect global increases in the speed of all the information processing.

For example, Kail (1992b) conducted two studies, each of which included a group of 9-year-old children and a group of young adults tested on measures of processing speed (including the coding subtest from the WISC-R, a number comparisons task, and a picture matching task) and memory span (including digit span, letter span, and free recall). In the second study, rate of articulation was also measured. Path analyses revealed that, in both the studies, the age-related differences in memory span could largely be explained by age-related differences in processing speed. When the articulation rate was added to the path model in the second study, a large portion of the age-related improvement in speech rate was mediated by age-related differences in the processing speed.

These results have been replicated in a subsequent study conducted by Kail and Park (1994) using groups of children and adults from US and from Korea.

Notably, one sample of children tested by Kail and Park showed a significant direct path between age and working memory indicating that age-related differences in speed did not account for all of the improvement in working memory. Kail and Park suggested that in addition to maturational changes in speed there may also be experiential or other maturational factors driving improvements in working memory. One possible explanation they proposed was that age-related improvements in children's use of rehearsal or retrieval strategies may be responsible for the weak, but significant direct path between age and memory span.

Also relevant here may be Kail's (Kail, 1992b) speculation that although most of the developmental increases in articulation rate may be due to global increases in processing speed, increases in word familiarity may also play a contributing role. This speculation regarding the role of familiarity is supported by the results of a study that examined the extreme case: words versus nonwords. This study showed that for both 6- and 10-year-olds, memory span for nonwords was consistently lower than one would expect based on the rate at which such items were articulated (Roodenrys et al., 1993).

A recent study conducted by Cowan et al. (Cowan et al. 1998, Experiment 1) also provides evidence suggesting that age-related improvements in memory span are not simply the results of improvements in a global speed factor. In particular, Cowan et al. (1998) examined the role of the rate of covertly rehearsing words in short-term memory (as measured by the rate of articulation) and the rate of retrieving words from short-term memory (as measured by the duration of the pauses between memory items during recall on the span task). The participants in this study were first-, third-, and fifth-grade children.

The key findings in this study were that articulation rate and pause duration during output were not correlated with each other even though both speed measures were correlated with memory span. A path model using latent constructs revealed that nearly all of the age-related variance in memory span could be accounted for by the two speed constructs. A comparison model in which only a single speed factor was used to predict the age-related improvement in memory span left approximately 15% of this variance unexplained. Thus, the results of this experiment add improvements in the rate of word retrieval to improvements in word familiarity as moderators of the well-documented relation between age and memory span.

Whereas Cowan et al.'s (Cowan et al. 1998) data suggest a possible need to decompose the effect of age-related improvements in speed on memory span into at least two separate speed factors, the results of a recent study by Chuah and Maybery (1999) provide additional support for a global speed factor. In their study, Chuah and Maybery administered a set of verbal and spatial tasks to a group of children between the ages of 5 and 12 years. The verbal tasks assessed verbal processing speed, articulation rate, and verbal memory span. The spatial tasks assessed spatial processing speed, a form of tapping rate designed to be analogous to the measurement of articulation rate, and spatial memory span.

Four major regression analyses were conducted using verbal and spatial span as the criterion variable and the remaining variables as predictors. In general, these analyses revealed results similar to those of Kail's studies; processing speed and articulation/tapping rate were good predictors of memory span. The results of special relevance, however, are that verbal processing speed predicted spatial span as well as it predicted the verbal span, and that both the spans were also predicted approximately as well by spatial processing speed. Thus, at least in terms of the basic dichotomy between the verbal and spatial domains, there appears to be no reason for additional decomposition of processing speed for the purpose of understanding the development of memory span.

An additional finding from Chuah and Maybery (1999) is worth noting. Contrary to findings from the study conducted by Kail and Park (1994) but consistent with Kail (1992b), the primary analyses of Chuah and Maybery's data did not reveal a unique contribution of age to the prediction of either verbal or spatial span. That is, almost all of the age-related improvements in verbal and spatial spans were jointly accounted for by processing speed and articulation/tapping rate.

## 8. Age, working memory, and intelligence

We have found only two recent articles (Cohen and Sandberg, 1980; Cornoldi et al., 1995) that focus exclusively on the relationship of working memory to intelligence in children, and neither of these included age as a variable. This lack of relevant research on children is surprising, given the recent interest in the relationship of individual differences in working memory and intelligence. For example, Just and Carpenter (1992) have proposed a capacity theory of working memory in which individual differences in the working memory are the consequence of differing levels of available activation. The greater the capacity of an individual's working memory, the more information the individual has simultaneously available for use in solving problems. This theory has been applied to both the verbal comprehension (Just and Carpenter, 1992) and figural pattern recognition such as that required by the Raven's Progressive Matrices (Carpenter et al., 1990).

With respect to comprehending verbal information, Just and Carpenter (1992) argued that the individuals with greater comprehension ability were those individuals who could better infer relationships and derive expectations based on linguistic cues. More importantly, however, those with greater comprehension ability also were better able to maintain activation of those inferences and expectations throughout the reading or hearing of a sentence. Presumably, individuals of lesser ability must reallocate activation resources to cope with additional incoming information, and therefore, lose any benefit they might have derived from maintaining linguistic information from earlier in the sentence in working memory.

With respect to performance on Raven's Matrices, Carpenter et al. (1990) hypothesized that those individuals who obtain higher scores are those individuals who are best able to induce relationships and develop, maintain, and manage problem-solving goals in working memory. Individuals of lesser ability are able to detect a variety of patterns and relationships. In contrast to the higher ability individuals, when they are forced to compare these relationships in a goal-oriented manner (and thereby induce more subtle abstract relationships), they presumably are unable to do so. According to Carpenter et al. (1990) this is because of insufficient activation resources to maintain all the representations in working memory at once.

Although this theory was formulated to explain the performance of adults, it nonetheless lends itself to the interpretation of age-related differences with respect to working memory and intelligence. Indeed, Just and Carpenter (1992) noted that the age-related decreases in verbal comprehension that are seen in late adulthood may be viewed as the direct consequence of reduced activational resources. As adults grow older, their levels of activation may decrease, leading to a reduction in their capacity to hold onto and integrate more difficult information. If one were to extend the Just and Carpenter framework to include children, one could argue that as children mature they develop an increase in activational levels and working memory capacity that ultimately results in improved intellectual functioning. Although this position was never stated explicitly by Just and Carpenter, there is some evidence that some of the assumptions underlying their theoretical framework certainly hold for children, as well as adults (i.e. Cohen and Sandberg, 1980; Cornoldi et al., 1995).

One of these assumptions is that the processing demands of a task must be high in order to distinguish individuals of differing abilities. Consistent with this assumption, Just and Carpenter (1992) found that groups of high-, medium- and low-span young adults performed differently on verbal comprehension tasks when the load on the working memory was relatively high; this relative difference in performance between the ability groups was much smaller when the load on the working memory was low. Cohen and Sandberg (1980) have reported similar results with children. They tested 13-year-old children on four different types of working memory tasks. Each memory task was given at two presentation rates: one slow and one fast. In addition, all the children had been administered a group IQ test battery (the Swedish DBA test) 2 months prior to the working memory tasks.

A factor analysis of the working memory scores separated the tasks into two classes; those tasks placing multiple demands on working memory (i.e. encoding items while holding additional information in memory) and those tasks requiring item identification (i.e. a lesser load on working memory). Cohen and Sandberg (1980) found that IQ loaded heavily on the first (i.e. multiple demands) working memory factor and only weakly on the second (i.e. item identification) factor. The correlations between IQ and working memory measures from the first factor ranged from.46 to.59. The authors concluded that working memory is more highly related to IQ in children if it is assessed when relatively greater (or multiple) demands are placed on the system.

Another assumption of the Just and Carpenter (1992) capacity theory is that different domains of processing (e.g. verbal, quantitative, spatial) may draw on different pools of activation and thus have different capacities with respect to working memory. For example, capacity with respect to verbal processing may be different than capacity with respect to figural problem solving such as that involved in the Raven's. Although not explicitly stated by Just and Carpenter, such an assumption implies that an individual might have strengths in one area (e.g. verbal working memory and verbal comprehension) but not necessarily in another area (e.g. visuospatial working memory and figural problem solving). Following this logic, one would conclude that the capacity from one domain is not necessarily transferable to another domain.

Cornoldi et al. (1995) conducted a study with children that is relevant to this issue. They tested groups of 6th- and 8th-grade children with two ability groups within each grade. One ability group consisted of children who had normal verbal intelligence but below average visuospatial intelligence (as measured by the verbal and the visuospatial subtests of the Primary Mental Abilities test). The other group was matched on verbal intelligence with the first group, but had normal (i.e. average) visuospatial intelligence.

Working memory was assessed using a battery of verbal and visuospatial working memory tasks (including verbal and visual puzzles, item and location recall within a matrix, and recall of initial and moving positions of cubes within a matrix). Cornoldi et al. (1995) found that the working memory for visuospatial information was significantly lower for the low visuospatial children than for the average visuospatial children. Consistent with their average verbal intelligence, however, the low visuospatial children showed average verbal working memory abilities. Interpreting these results with respect to the Just and Carpenter (1992) working memory framework, one would conclude that children have separate working memory resources for different domains, although in so far as individuals with high activation levels in one domain are also likely to have high activation levels in another domain, one might expect correlations between working memory and intelligence across domains.

The strong relationship between working memory ability and intelligence might appear to suggest that the conscious contents of working memory provide the bases for reasoning and problem solving. Brainerd and his colleagues (Brainerd and Kingma, 1985; Brainerd and Reyna, 1990, 1993), however, have repeatedly argued that reasoning does not depend on the contents of working memory, at least as assessed by tests of verbatim recall. Rather, they contend that reasoning is based on gist representations of problem information, particularly in children but also in adults.

The correlation between performance on working memory tests and tests of fluid intelligence is a robust phenomenon (e.g. Kyllonen and Christal, 1990; Fry and Hale, 1996) that requires an explanation regardless of whether or not Brainerd and his colleagues are correct as to the kind of memory (gist vs. verbatim) involved in reasoning. If they are correct about reasoning, however, then the correlation between working memory measures and intelligence has a 'third cause' explanation. That is, the ability to form and maintain gist representations and the ability to maintain verbatim information of the sort assessed on working memory tasks may be positively correlated, and if so then it may be the variance shared between the gist and verbatim memory that underlies the relation between working memory and intelligence.

For the present, however, it should be noted that there is currently no consensus on the type of memory involved in reasoning (compare Brainerd and Reyna, 1992 with Chapman and Lindenberger, 1992). Moreover, the question of how the type of reasoning studied by Brainerd and colleagues is related to the type of reasoning assessed by tests of fluid intelligence (e.g., Ravens) remains unresolved. Thus, the general issue of what types of information need to kept accessible while engaged in what types of reasoning remains an important topic for future research.

## 9. Age, speed, working memory, and intelligence

Like Just and Carpenter (1992), Kyllonen and Christal (1990) have argued that working memory ability is a determinant of reasoning ability, but in addition, they have examined the relation of processing speed to both these abilities. In four experiments with a total of over 2000 young adults and using a wide variety of working memory tasks, Kyllonen and Christal found that not only was working memory highly correlated (i.e. *rs* of 0.82–0.88) with reasoning ability as measured by the ASVAB battery (a measure of intelligence similar to the WISC-R) but also that processing speed was moderately correlated to working memory (i.e. 0.35–0.48). Thus, in young adults there appears to be a relationship between individual differences in speed, working memory, and intelligence.

There is only one comparable study, by de de Jong and Das-Smaal (1995), of speed, working memory, and intelligence in children. Unfortunately from the current perspective, only one age group (9-year-old children) was tested. However, the findings do suggest that the relationship among individual differences in speed, working memory, and intelligence is essentially the same in children as it is in adults. Using tasks and analytic procedures similar to Kyllonen and Christal (1990), de Jong and Das-Smaal (1995) found a strong correlation between processing speed and working memory (i.e. $r = 0.60$), as well as a strong correlation between working memory and fluid intelligence (i.e. $r = 0.66$).

Only two studies have directly examined the effect of age on the interrelationships among speed, working memory, and intelligence in children, one by Miller and Vernon (1996) and the other by the current authors (Fry and Hale, 1996). Our study used a cross-sectional design to examine changes in these variables between 7 and 19 years, whereas Miller and Vernon studied a much narrower age range (4 years, 0 months to 6 years, 12 months). This age-range, however, also represents a major strength because Miller and Vernon focus on relatively early cognitive development. As will be seen, the two studies measured the same set of constructs with fairly similar instruments given the differences in the age ranges involved. Although, there are certain similarities in the patterns of data reported in these two studies, the authors nonetheless reached rather different conclusions regarding the causal developmental links between processing speed, working memory, and fluid intelligence.

Fry and Hale's (Fry and Hale, 1996) study was designed to examine the extent to which the age-related improvements in fluid intelligence observed in children and

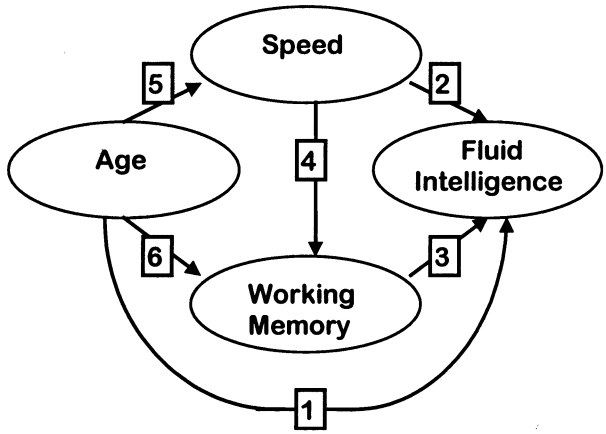


Fig. 4. Developmental cascade model indicating the six possible causal links.

adolescents are the product of age-related improvements in processing speed and working memory capacity. More specifically, our study posited a causal model, which we termed the *developmental cascade model*. A schematic diagram of this model is provided in Fig. 4. Note that in the full developmental cascade model, age, processing speed, and working memory are potential predictors of fluid intelligence (paths 1, 2, and 3, respectively). In addition to serving as a predictor of fluid intelligence, processing speed is shown as a potential predictor of working memory (path 4). Finally, age (which is a surrogate variable for unspecified maturational or experiential variables) is shown as a potential predictor of both speed and working memory (paths 5 and 6, respectively).

Note that only those paths that are in keeping with the current hypotheses and the empirical findings described above are included in the model. That is, although speed has been hypothesized to be a determinant of working memory capacity (Kail, 1992b) and both speed and working memory have been hypothesized to be determinants of fluid intelligence (Kail and Salthouse, 1994), neither fluid intelligence nor working memory have been hypothesized to be determinants of speed nor has fluid intelligence been hypothesized to be a determinant of working memory. Finally, although age is known to be correlated with speed, working memory, and fluid intelligence (Cerella and Hale, 1994), these variables obviously cannot be causal with respect to age.

A total of 219 participants, 169 children and 50 young adults, were tested in the Fry and Hale (1996) study. All the participants were tested on a battery of four speeded information-processing tasks, four working memory tasks, and a computerized version of the Raven's Standard Progressive Matrices. The processing speed tasks were modified versions of the set of four nonlexical tasks used previously by Hale (Hale, 1990; Hale et al., 1993): disjunctive arrows, shape classification, visual search, and abstract matching. These four tasks differ both in terms of the putative cognitive components recruited during performance and in terms of task complexity. Nevertheless, Hale and Jansen (1994) have shown that individuals are approximately the same percentage faster or slower than average on all of these tasks and that it is, therefore, possible to derive a task-independent index of an individual's processing speed.

Fry and Hale (1996) measured working memory using verbal and visuospatial memory span tasks presented both with and without interleaved secondary tasks. The procedures, developed originally by Hale et al. (1996), involved the presentation of multiple series of two to nine target items (either Xs or digits) followed by recall. The primary tasks required participants to hold either the locations of the Xs or the identities of the digits in working memory while the interleaved secondary tasks required them to recognize and report, either manually or vocally, the colors of the items. For the current purposes, we simplified the Hale et al. (1996) procedures so as to make it easier to teach the task to 7- and 8-year-old children. In particular, we increased the duration of the presentation of each item to 2 s and decreased the number of colors used in the secondary task conditions to three (i.e. red, white, and blue). The inter-item interval was 750 ms, and the interval between each series was self-paced.

Path analyses were conducted using Bentler's Structural Equations Program (EQS; Bentler, 1989) in order to examine possible causal relations between age, processing speed, working memory, and fluid intelligence. Preliminary analyses established that the various processing speed and working memory measures (i.e. the different RT tasks and working memory conditions) should be weighted equally in making up the relevant speed and memory composites. In addition, analyses involving pairs of the age, speed, working memory, and intelligence variables were conducted in order to determine how to linearize the relations between them. Based on the results of these preliminary analyses, the path analyses were conducted using the logarithm of chronological age, a composite of the logarithms of the $z$ scores for the four processing speed measures, a composite of the $z$ scores for the four working memory measures, and the raw Raven's score.

The results of the path analysis of the developmental cascade model are presented in Fig. 5. The numbers imposed on each path from the causal variable to the dependent variable are the standardized path coefficients indicating the change in the dependent variable, in S.D. units, expected to occur from a change of one S.D. in the causal variable when all other variables are held constant. In addition to significant paths between age and speed, speed and working memory, and working memory and fluid intelligence, two additional paths remained in the model: the path linking age to working memory and the path linking age to fluid intelligence. The coefficient for the path linking speed directly to fluid intelligence is indicated in the figure even though this path did not reach statistical significance (i.e. it failed the Wald Test for inclusion). Retesting the model with the path from speed to fluid intelligence omitted resulted in negligible increases in the coefficients for the paths from working memory to fluid intelligence and from age to fluid intelligence.

Since the publication of Fry and Hale (1996), we have conducted additional analyses to partial out the unique and shared variances among age, speed, and working memory and among age, working memory, and fluid intelligence. To this

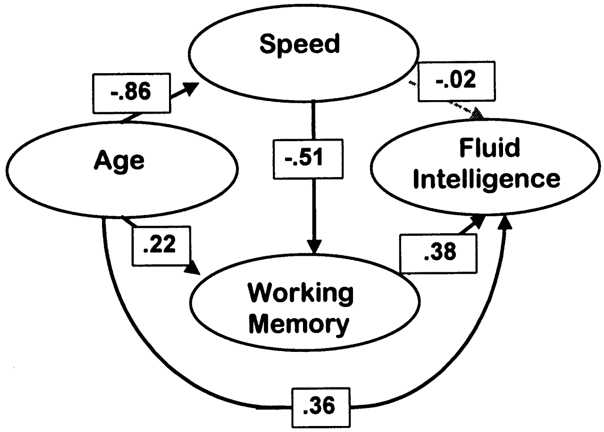


Fig. 5. Path coefficients for the developmental cascade model. The path from speed to fluid intelligence, shown in gray, failed the Wald test. Re-testing with that path omitted resulted in negligible changes in the path coefficients.

end, two hierarchical multiple regressions were conducted for each set of variables. These analyses revealed that nearly all of the variance in working memory that could be accounted for by age was shared variance (i.e. variance shared between age and speed). Additionally, most of the variance in fluid intelligence that could be accounted for by age was also shared variance (i.e. variance shared between age and working memory). That is, even though the paths from age to intelligence and from age to working memory were significant, the amount of the age-related variance accounted for by these paths was relatively small. Specifically, only 3% of the total age contribution to working memory was independent of speed, and only 20% of the total age-related differences in fluid intelligence were not mediated by speed and/or working memory.

Finally, we turn to the recent study by Miller and Vernon (1996) who assessed 109 young children using a computerized battery of eight processing speed tasks and five working memory tests, as well as fluid intelligence was measured using the Wechsler preschool and primary scale of intelligence-revised (WPPSI-R). The eight processing speed tasks were shape judgment (same or different), color judgment (same or different), size judgment (same or different), number judgment (same or different quantity), shape memory (varied mapping visual search), color memory (similar to the shape memory task), arrow-direction judgment (left or right), and delayed matching (two sample stimuli were presented side by side followed by a single probe item).

All five of Miller and Vernon's (Miller and Vernon, 1996) working memory tests were designed to assess the longest sequence of items a child could recall correctly. The number of items to be recalled varied from two to seven. As in Fry and Hale (1996), the procedure for each of the working memory tests followed the standard administration of the digit span subtest of the WISC-R: Two lists of items were presented at each series length (beginning with two items) until a child failed to

Table 1
Intercorrelations of age, processing speed, working memory, and intelligence reported by Fry and Hale (1996) and Miller and Vernon (1996)[a]

| | Age | Processing speed | Working memory | Intelligence |
|---|---|---|---|---|
| Age | | −0.86 | 0.66 | 0.63 |
| Processing speed | −0.41 | | −0.70 | −0.60 |
| Working memory | 0.64 | −0.44 | | 0.64 |
| Intelligence | 0.78 | −0.42 | 0.82 | |

[a] Values above the diagonal are from data reported in Fry and Hale (1996) and values below the diagonal are from Miller and Vernon (1996). Correlations associated with processing speed are negative because speed was measured using reaction times in both of these studies.

recall both lists at a given series length. The five memory span tests were, (1) a sequential color span task (stimuli were red and yellow squares), a simultaneous color span task (identical to the sequential version except that the squares were presented simultaneously), a sequential shape span task (identical to the sequential color span task except that the stimuli were green squares and green triangles), a simultaneous shape span task (identical to the simultaneous color span task except that the stimuli were the same as in the simultaneous shape span task), and a tone span task (sequential presentation of two different tones — one low and one high). For the color and shape sequential versions of the memory span tasks, each item in the series was presented for 750 ms and there was no inter-stimulus interval. For the color and shape simultaneous versions of the memory span tasks, the presentation time was equal to the number of items presented times 750 ms. Finally, for the tone span task, each tone was presented for 500 ms with a 100 ms inter-stimulus interval.

Despite the difference in the ages of the samples, the minor procedural differences, and the use of different tests of intelligence, the patterns of correlations obtained by Miller and Vernon (1996) were similar to those in the Fry and Hale (1996) study. As can be seen in Table 1, however, a direct comparison of the values obtained from each of studies reveals that all three correlations involving processing speed were substantially weaker in the Miller and Vernon study.

Although Miller and Vernon (1996) did not conduct a path analysis, they did conduct multiple regression analyses with scores on the WPPSI-R as the criterion variable. These analyses revealed that no significant increase in $R^2$ when speed was added after memory in the regression model. In contrast, the increase in $R^2$ when memory was added after speed was both substantial and significant. Based on these results, Miller and Vernon concluded that there was only a weak relationship between speed and intelligence and suggested that models of adult intelligence in which speed is thought to play a greater role (e.g. Kyllonen and Christal, 1990) may not be appropriate for describing intelligence in very young children.

It is important to point out that one *might* have drawn similar conclusions from the Fry and Hale (1996) study had we not conducted a path analysis and analyses to decompose age-related differences. That is, similar to Miller and Vernon (1996), our multiple regression analyses also revealed that working memory performance was a better predictor of fluid intelligence than speed. Only through path analyses and decomposition of the variances did we discover that, although working memory was very important, nearly all of the age-related differences in working memory were due to age-related differences in speed.

This was the case both when the data from the entire Fry and Hale (1996) sample were analyzed (and 97% of the age-related differences in working memory were accounted for by age-related differences in speed) and when only the data from the children were analyzed (and 88% of the age-related differences in working memory were accounted for by age-related differences in speed). The latter finding clearly demonstrates that the important putatively causal role played by age-related differences in speed in the determination of working memory differences was not dependent on the presence of young adults in the analysis.

## 10. Conclusions and future directions

Careful consideration of the literature on processing speed, working memory, and fluid intelligence in children reveals that there are three different issues with respect to the interrelations between these variables. The first issue concerns the time course of developmental increases in cognitive ability. The second issue concerns how age impacts individual differences in speed, working memory, and intelligence, particularly with respect to its effect on the correlations between these variables. The third and final issue concerns the mechanisms by which developmental increases in different aspects of cognition affect each other.

The data are clearest with respect to the first of these issues. Studies in which one of the three cognitive variables (processing speed, working memory, and fluid intelligence) were measured as a function of age have almost universally found relatively precise nonlinear growth functions. Not only do these functions have the same form, but also they strongly suggest that all the three cognitive variables develop in concert, raising the question of why they are so precisely linked. It is important to recognize, however, that linkage at the level of group averages does not necessarily imply linkage at the level of the changing abilities of individuals. Therefore, we turn next to the second issue, that of possible age-related differences in the pattern of individual differences among peers.

Studies that have examined speed and intelligence in different age groups of children have yielded a wide range correlations between these two constructs. This range is similar to that observed with adult samples, however, and there is little evidence of systematic change in the strength of the correlation between speed and intelligence with age. Unfortunately, comparable data on the correlations between speed and working memory or between working memory and intelligence at different ages are not available. The few studies that have examined these relationships have used multiple age groups, and the sample sizes at each age have been relatively small for correlational research on individual differences. Accordingly, such studies have not reported correlations by age group, and future research is needed to fill this gap.

The third issue, which concerns the mechanisms by which developmental increases in different aspects of cognition affect each other, actually represents a set of issues. With respect to one of these, the effect of age-related increases in speed on working memory, the evidence suggests that the effect of speed is indirect, at least in the case of school-age children and verbal working memory. In this case, speed appears to exert its influence via its effect on the rate of covert rehearsal as indexed by articulation rate (Kail, 1992b; Kail and Park, 1994). With respect to another of these issues, the effect of age-related increases in working memory on intelligence, the evidence suggests that much of the age-related increase in intelligence test scores may be attributed to developmental improvements in working memory (Fry and Hale, 1996; Miller and Vernon, 1996).

Turning to yet another issue regarding developmental mechanisms, the evidence suggests that a similar account seems to hold for the effects of both age-related increases in speed and working memory on intelligence. That is, much of the age-related improvement in intelligence test scores appears to be due to increases in speed (Fry and Hale, 1996), although in pre-school children, the relationship between speed and intelligence may be much weaker than that between working memory and intelligence (Miller and Vernon, 1996). Importantly, virtually all of the effect of the age-related increase in speed on intelligence appears to be mediated through the effect of speed on working memory (Fry and Hale, 1996), as suggested by Kail and Salthouse (1994). Moreover, virtually all of the effect of improvements in working memory on intelligence is itself attributable to the effect of improvements in speed on working memory, providing further evidence of a cognitive developmental cascade (Fry and Hale, 1996).

In the past, developmental researchers have considered maturation as a kind of default variable, one that is less open to interpretation. Its status as a variable is likely to change, however, as a result of current and future advances in cognitive neuroscience. That is, it used to be the case that the evidence for maturation would be primarily negative, consisting of the exclusion of candidate experiential mechanisms. In the near future, however, the exploration of potential maturational factors may involve empirical evaluation of possible neurobiological substrates. For example, one possible mechanism that might underlie the 20% of the age-related variance in fluid intelligence not explained by changes in speed or working memory in the Fry and Hale (1996) study, involves the developmental changes in frontal cortex that take place during childhood and adolescence (Goldman-Rakic, 1987; Dempster, 1992). Including measures of cortical function based on neuroimaging in future studies could permit empirical evaluation of this and other hypotheses, thereby opening the door to a whole new era in the study of cognitive development.

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