Available online at www.sciencedirect.com

SCIENCE DIRECT®

Intelligence 33 (2005) 93–106

INTELLIGENCE

Rising mean IQ: Cognitive demand of mathematics education for young children, population exposure to formal schooling, and the neurobiology of the prefrontal cortex

Clancy Blair[a,*], David Gamson[b], Steven Thorne[c], David Baker[d]

[a]*Human Development and Family Studies, Pennsylvania State University, 110 Henderson South, University Park, PA 16802-6504, United States*
[b]*Department of Education and Policy Studies, Pennsylvania State University, United States*
[c]*Department of Linguistics and Applied Language Studies, Pennsylvania State University, United States*
[d]*Departments of Education Policy Studies and Sociology, Pennsylvania State University, United States*

Received 26 November 2003; received in revised form 26 May 2004; accepted 22 July 2004
Available online 3 October 2004

Abstract

This paper proposes one potential explanation for 100 years of rising population mean IQ in the United States associated with historical changes in access to schooling and educational practice. A neurodevelopmental-schooling hypothesis is forwarded based on evidence of growth in the population's access to schooling early in the last century and the increasing cognitive demands of mathematical curricula from mid-century onward. The fact that these educational changes have been widespread, affect individuals early in the lifespan, and are uncorrelated with genetic propensity for IQ makes them particularly well suited to produce large environmentally driven gains in intelligence between generations in the face of high heritability for intelligence. Future directions for research that would test the neurodevelopment-schooling hypothesis are described.

Keywords: IQ; Mathematics; Formal schooling; Prefrontal cortex

* Corresponding author. Tel.: +1 814 863 6423; fax: +1 814 863 6207.
E-mail address: cbb11@psu.edu (C. Blair).

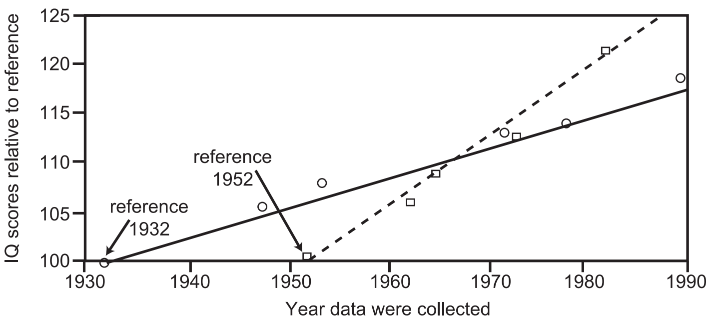
0160-2896/$ - see front matter © 2004 Elsevier Inc. All rights reserved.
doi:10.1016/j.intell.2004.07.008

1. Introduction

The mean level of intelligence in the world population, as assessed by standardized measures of mental ability, has risen rapidly since the turn of the 20th century (Flynn, 1984, 1987). For example, the estimated IQ of the average adult in 1930 was approximately one to two standard deviations below that of the average adult in the year 2000. As shown in Fig. 1, the mean IQ of the U.S. population as assessed by the Wechlser scale, a measure weighted toward the assessment of acculturated knowledge, also referred to as crystallized intelligence, has risen by approximately 20 points over the last 60 years. More impressive, however, are gains in measures such as the Raven's Progressive Matrices Test, a measure of reasoning ability as applied in novel contexts, also referred to as fluid intelligence. Gains on measures of fluid intelligence have been approximately double those on measures of crystallized abilities, with reported fluid gains in a population based sample in the Netherlands of 18–20 points in a single generation (Flynn, 1999).

Far too rapid to be caused by genetic selection, rising fluid skills among successive cohorts of adults over the past century must be associated with aggregate environmental processes. The significant impact of proximal environment on individual variation in IQ is well established and appears to be greatest in early childhood (Ceci, 1991; Ceci & Williams, 1997; Plomin, DeFries, McLearn, & Rutter, 1997; Ramey & Campbell, 1984). In accord with prior findings on the role of early experience in mental development, we develop here a hypothesis about one possible cause of rising population mean IQ that points directly to historical changes in access to schooling and changes in educational practice in the early elementary grades that have emphasized the instruction of fluid cognitive functions of the prefrontal cortex known to be associated with performance on IQ tests.

It is important to acknowledge at the outset, however, that the phenomenon of rising mean IQ and what it means for the study of intelligence is somewhat unclear. For one, the rise in IQ is difficult to



The rise in intelligence test scores since 1932. The solid line shows the adjusted mean performance of Americans on various Wechsler test as well as the Stanford-Binet; the dashed line shows the mean performance of 18 year-old Dutch males on a version of Raven's Progressive Matrices

Fig. 1. IQ increase over the 20th century.

reconcile with conclusions from psychometric and behavior genetic approaches to intelligence. Numerous studies indicate that measures of intelligence reliably produce a latent general factor, referred to as g, which is associated with real world competence and is highly heritable (see Jensen, 1998). However, analysis of measurement invariance between normative cohorts in gains on five standardized measures of intelligence indicated that IQ gains cannot be attributed to change in a general latent factor but primarily reflect systematic variation in specific aspects of cognition leading to bias between cohorts on a number of subtests of intelligence measures (Wicherts et al., in press). Something in the experience of successive generations is bringing about changes in aspects of cognitive functioning that are associated with g within but not between cohorts.

Although there are numerous explanations as to what has been causing the historical rise in mean IQ, many of which have merit, none have met several essential criteria required of a plausible explanation: (1) the environmental mechanism must be clearly associated with large gains in fluid cognitive skills; (2) large proportions of the population must have been exposed to the mechanism and exposure within cohorts must have been relatively uniform; (3) increasing numbers of individuals within cohorts must have been exposed over time; (4) exposure must have intensified over historical time matching the monotonic increase in population fluid IQ; and (5) change in exposure between cohorts must be large relative to variance in exposure within cohorts.

In an attempt to meet these criteria, our hypothesis develops the argument for a putative mechanism of change that directly impacts the area of the brain most directly associated with fluid test taking skills, the prefrontal cortex (PFC). Aspects of experience that exercise prefrontally based fluid skills would be likely to lead to gains in IQ test performance over time. Specifically, we suggest that two widespread environmental mechanisms led to an increase in measured intelligence across the population: (1) access to formal schooling expanded for successively larger proportions of cohorts of young children early in the 20th century; and, (2) the fluid cognitive demand of mathematics curricula for young students increased from mid-century onward. It is likely that these mechanisms in combination contributed to mean increases in measured intelligence over the past 100 years.

We first review evidence demonstrating the role of the PFC in fluid cognitive functions. We then review evidence indicating that PFC development during childhood is relatively slow compared to other brain regions and exhibits a high degree of neural plasticity in response to experience. Then we present evidence of the increase in access to schooling over historical time and an increase in the fluid cognitive demand of mathematics curricula for young students. Lastly we assess this neurodevelopmental-school exposure hypothesis relative to the criteria for an environmentally driven change in population IQ in the face of high heritability for intelligence (Dickens & Flynn, 2001).

2. Neurobiology of the prefrontal cortex (PFC)

A number of psychometric examinations of the structure of intelligence have indicated that fluid cognitive functioning, i.e., that relating to the active maintenance and coordination of information in short term store for the purpose of goal directed activity (working memory, broadly defined) is central to performance on measures of general intelligence and highly correlated with estimates of psychometric g (Embretson, 1995; Gustafsson, 1984; Kyllonen, 1996). Furthermore, neuroimaging studies have shown that structures of the PFC that are the seat of fluid cognitive processes are also central to performance on measures of general intelligence (Gray, Chabris, & Braver, 2003). Examinations of prefrontal cortical activation patterns associated with the working memory demand of various cognitive measures have indicated increases in dorsolateral prefrontal activation with increases in the working memory load and/or g-loading of a given cognitive task (Braver et al., 1997; Duncan et al., 2000; Prabhakaran, Narayanan, Zhao, & Gabrieli, 2000; Prabhakaran, Smith, Desmond, Glover, & Gabrieli, 1997).

Similarly, clinical neuropsychological and computational modeling studies of fluid intelligence have demonstrated that performance on measures of fluid intelligence such as the Raven's test (see Fig. 2) are dependent upon the ability to hold two or more relations active in working memory when solving test items (Carpenter, Just, & Shell, 1990; Waltz et al., 1999). In fact, clinical populations of adults with damage to the prefrontal cortex exhibit scores on the Raven's test that are one to two standard deviations below their performance on measures primarily assessing crystallized abilities (Duncan, Burgess, & Emslie, 1995; Waltz et al., 1999). In essence, although the intelligence of adult clinical populations with prefrontal cortical trauma as assessed by measures such as the Wechsler battery is in the normal range, intelligence as assessed by the Raven's test is in the range of mental retardation.

In the study of the development of the PFC, clinical and experimental brain research have demonstrated that the PFC undergoes protracted postnatal development in response to experience from birth through young adulthood (Benes, 2001; Bourgeois, Goldman-Rakic, & Rakic, 1994). Expansion of

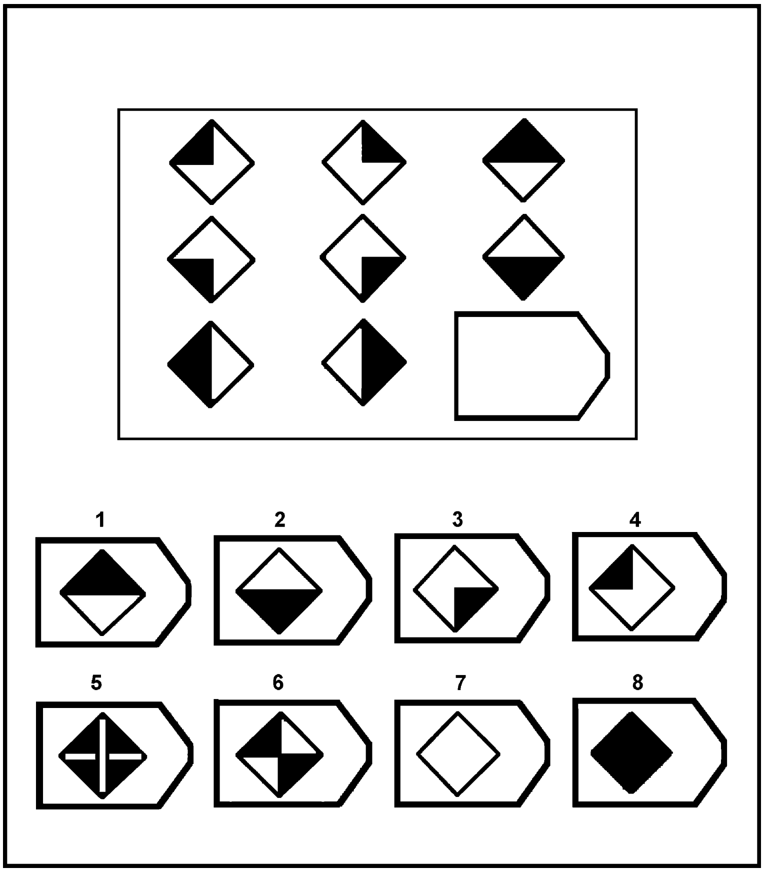


Fig. 2. Problem illustrating the Raven's Progressive Matrices Test.

the prefrontal cortex in humans and great apes is phylogenetically recent (Semendeferi, Lu, Schenker, & Damasio, 2002) and marks the emergence of a brain area characterized by an extended period of use dependent synaptogenesis and synaptic stabilization known to underlie learning and memory processes (Goldman-Rakic, Bourgeois, & Rakic, 1997).

In accord with evidence regarding prefrontal cortical structural development and function, we propose that changes in aspects of experience associated with the utilization and repeated practice of prefrontally based fluid cognitive skills that begin relatively early in life are likely to lead to relatively enduring changes in performance on measures of fluid intelligence. Taken together, evidence indicating that the PFC is the seat of fluid cognitive functions and undergoes protracted postnatal development suggests that population wide influences on prefrontal skill acquisition between cohorts would lead to increasing population mean IQ as observed by Flynn (1984, 1987). Differences between cohorts in experiences related to the development of fluid cognitive functions would be expected to increase mean levels of performance on measures of fluid intelligence over historical time but not necessarily affect population mean levels of crystallized intelligence or individual differences in fluid or crystallized intelligence as observed at any one point in time.

3. Population exposure to formal mathematics education

Formal schooling is a mass medium by which successively larger proportions of cohorts of young children over the 20th century have been exposed to a type of training that is explicitly related to population increases in fluid cognitive skills. Substantial evidence of the effects of school attendance on the development of IQ has existed for some time. A detailed review of over 50 studies using naturalistic observation, post-hoc statistical comparisons, and cohort-sequential analysis concludes that there is an association between enhancement of cognitive skills related to IQ and schooling (Ceci, 1991). These studies, conducted throughout the 20th century, comparing schooled and non-schooled populations, have estimated that the enhancement of IQ by schooling ranges from 0.3 to 0.6 of an IQ point for every year of school competed. Importantly, the association between IQ and exposure to formal education is not only due to children with higher measured IQ staying in school longer. By comparing similar children (e.g., equal on family social background and initial IQ) with different exposures to schooling, these studies support a causal relationship between attending even minimal amounts of schooling and the development of intelligence.

As shown in Fig. 3, schooling for primary-and kindergarten-aged children approaches universal enrollment over the first half of the 20th century. In economically developed nations like the US, the implementation of mass schooling progressed over the 20th century in terms of both exposure of larger proportions of a birth-cohort to some schooling and an increase in the total average years in school (Rubinson & Fuller, 1992). In the first three decades of the 20th century, significant proportions of adults who took IQ tests had little or no formal schooling. The growth in exposure to school, particularly through the addition of kindergarten and near-universal elementary school enrollment, is consistent with increasing mean IQ in the population over the middle decades of the century.

However, for intelligence, specifically fluid intelligence, to continue to grow among successive cohorts in the second half of the century, the effect of schooling would have had to intensify beyond the effects of full cohort enrollments and longer school careers. Expanding schooling has been previously considered as a possible explanation for rising mean fluid intelligence, but it has foundered to some

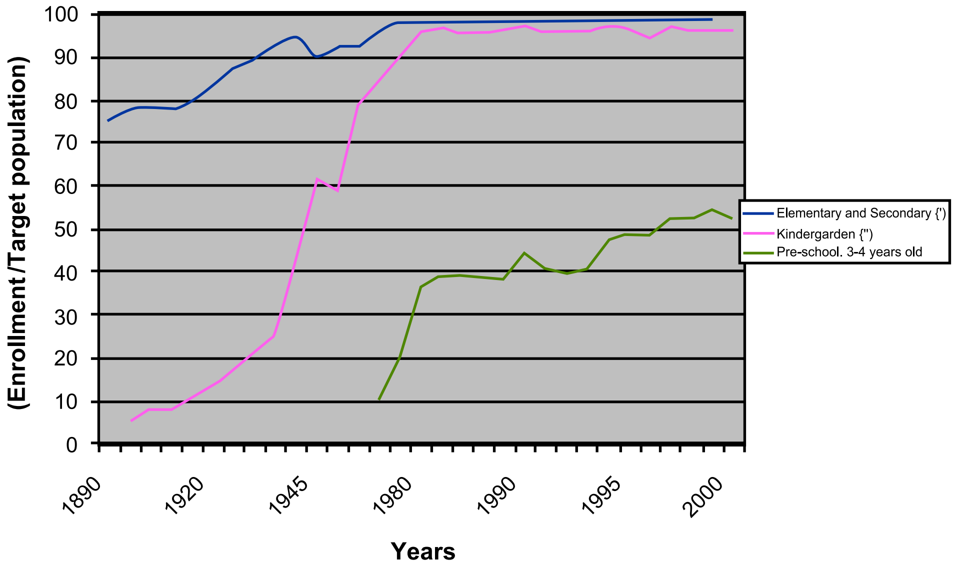


Fig. 3. School enrollment over time.

extent on the absence of a potential intensifying causal factor that matches population increases from the mid-century on (Flynn, 1998). Specifically, given near full enrollment by mid-century, something in the process or content of schooling itself must have been changing that enhanced fluid cognitive skills. Prior reviews have identified direct effects of schooling on fluid cognitive skills. Ceci (1991) reviews several cross-cultural studies indicating effects of schooling on fluid cognitive functions. And Williams (1998) has identified increased exposure to geometric figures, patterns, and pictorial representations of information both in and out of school as a potential contributor to rising mean IQ. Our thesis builds on this prior work to consider changes in math education in the early grades as a central mechanism through which schooling broadly affected fluid skills development in the population over time.

4. History of mathematics curricula and materials

Although many aspects of formal schooling are relevant to the cognitive functions of the PFC, no one area of the curriculum would appear to focus so directly on the exercise of fluid cognitive functions as does mathematics in the early elementary grades. And no aspect of formal schooling would appear to show the substantial and increasing emphasis on fluid cognitive skills as has early elementary mathematics. Experimental and differential studies of math achievement in typically developing children and children with learning disorders indicate the importance of fluid cognition for math ability (Bull & Scerif, 2001; Evans, Floyd, McGrew, & Leforgee, 2002; McGrew & Hessler, 1995; McLean & Hitch, 1999). Similarly, brain imaging research with typically developing adult populations indicate prefrontal activations associated with multiple operation problems (Kazui, Kitagaki, & Mori, 2000; Prabharakan, Rypma, & Garbrieli, 2001).

Before examining the historical increase in the fluid cognitive content of early math education in the US, however, it is important to note that an increasing emphasis on fluid skills in early math education as an explanation for rising mean IQ presents a paradox. Specifically, mathematics reasoning ability is one of the few aspects of intelligence to show almost no historical change over the past 50 years. Gains on the Wechsler arithmetic subtest are small to none while changes in math achievement as tracked in a number of national studies reveal increases over time that are moderate, although there is evidence that the size of the increase in US mathematics achievement has been underestimated in some prior research (Grissmer, 2000; Grissmer, Williamson, Kirby, & Berends, 1998).

Importantly though, while mathematics textbooks for use in the early elementary grades ostensibly imply a focus on numbers and arithmetic operations, our historical examination of early childhood US mathematics curricula, specifically from 1960 to 2000, indicate a significant focus on fluid cognitive reasoning tasks such as pattern recognition and pattern completion tasks (for example, see Figs. 2 and 4, panels C and D). K-3 mathematics curricula over time have increasingly included a range of these 'culture reduced' problem types such as those associated with the Raven's Progressive Matrices and the Performance subtests of the Wechsler batteries. It is the increase in the frequency of these problem types that exercise fluid cognitive skills, and not exposure to arithmetic knowledge per se, and that we correlate with the rise in measured fluid intelligence.

A detailed examination of widely used mathematics textbooks from the 1890s through the 1990s revealed that mathematics curricula in the early primary grades (K-2) evolved from a virtual vacuum. Almost no mathematics was offered to the youngest students during the early 1900s; in contrast, a broad and comprehensive curriculum existed for all primary grades by the 1960s. In addition to a progressive increase in the proportion of mathematics in K-2 curricula, educators introduced new types of cognitively challenging mathematics problems. For example, sophisticated geometry problems were consistently shifted downward throughout the century into textbooks designed for younger students.

Fig. 4 demonstrates the progressive increase, and intensification of, mathematics curricular items emphasizing fluid cognitive skills for younger ages since the middle of the century. Throughout the past 100 years, we find a progressive increase in the amount and type of material that requires children to solve problems by performing multiple sequential cognitive operations in a way that would be expected to exercise working memory. Assuming that literacy was a prerequisite for numeracy, educators in the late 19th century focused first on basic literacy skills, and most of the elementary mathematics textbooks published before 1895 consisted largely of prose with few symbols or diagrams (Clason, 1968). It was not until the 1920s that educators gradually began introducing mathematics materials designed for students in first or second grade.

At the turn of the 20th century, much of the mathematics instruction for children in the upper elementary grades was rigid, formalistic, and emphasized drill and rote memorization. For example, one educator who visited 36 urban school systems in the 1890s characterized mathematics instruction as patently absurd: "In no single exercise is a child permitted to think," he exclaimed. "He is told just what to say, and he is drilled not only in what to say, but also in the manner in which he must say it" (Rice, 1893, 38).

Rejecting drill and memorization as the principle modes of instruction, educators of the Progressive Era (1890s–1930s) developed mathematics problems for young children that focused on basic counting skills and the conception of number (see Panel 4a). Recognizing that young students could be taught mathematics through visual representation, educators in the 1930s developed curricula that moved beyond the simplest forms of counting and toward categorization and grouping (see Panel 4b). These

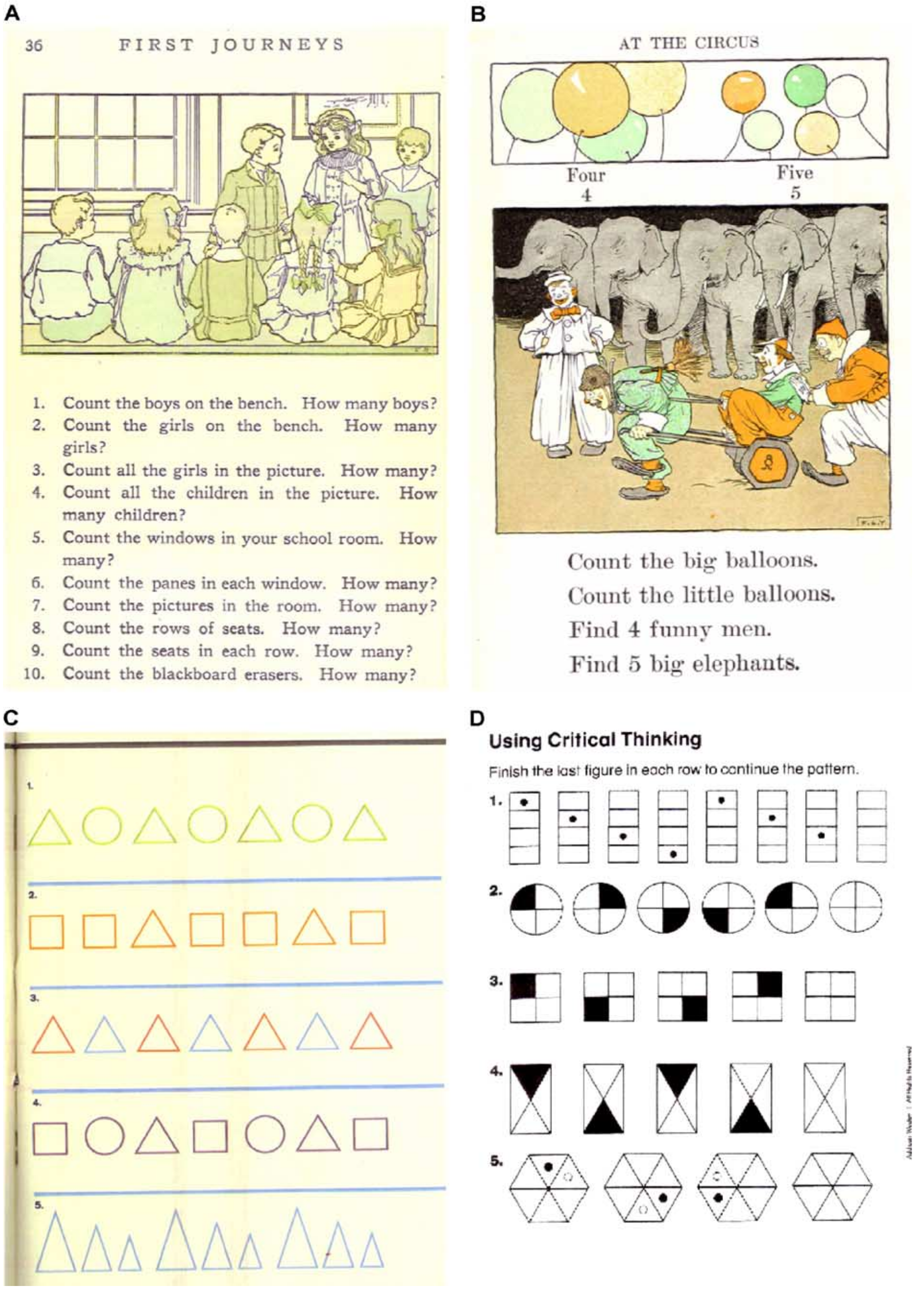


Fig. 4. Changes in mathematics texts, grades k-2.

examples represent the first serious and sustained efforts to teach first and second graders mathematical concepts. By the 1940s, series of mathematics textbooks often included separate volumes for kindergarten through the third grade and started to provide access to a variety of math-mediated cognitive tasks.

The 1950s and 1960s witnessed further significant changes in the way mathematics education was conceptualized. Nationally, mathematics instruction shifted away from a focus on algorithms and basic arithmetic problems (i.e., pages and pages of simple equations) and instead emphasized problems for young students in visual-spatial relations and the holding in mind of multiple operations in problem solving. Such problem types emphasize pattern recognition and pattern completion (see Panel 4C). The crisis of confidence in American mathematics and science education after the launch of *Sputnik* in 1957 accelerated the transformation of the mathematics curriculum in the 1960s (National Council of Teachers of Mathematics, 1970). While curriculum development efforts stalled somewhat in the 1970s, renewed national efforts to increase mathematics skill among young students in the 1980s and 1990s gave rise to dramatically different kinds of texts that are increasingly complex, comprehensive, and cognitively challenging (Nicely, 1991, Summer). Indeed, despite the widespread misconception that the quality of American schools has declined in recent decades, many reliable measures indicate that the reverse is true. Long-term trend analysis of mathematics achievement scores, for example, demonstrates that mathematics achievement in 1999 was higher than that in 1973 for all three assessed groups—9 year olds, 13 year olds, and 17 year olds (Campbell, Hombo, Mazzeo, & National Center for Education Statistics, 2000).

Fig. 4d shows a 1991 second grade text with a pattern recognition task that is very similar to that utilized by the well known Raven's Progressive Matrices Test (see Fig. 2). Here students are given practice and instruction in the types of problem solving tasks that directly exercise working memory and executive cognitive control functions of the prefrontal cortex. Importantly, this example is very similar to test items frequently used to measure fluid intelligence. The striking similarity between common mathematics problem types and items on widely administered intelligence tests suggests a convergence of changes in mathematics curricula and performance on measures of fluid cognitive skills. Essentially, problem types common to early childhood mathematics education have increasingly converged with the skills needed for IQ test items. We hypothesize that this convergence in part explains increases between generations in performance on measures of intelligence.

A second analysis of 20th century curricular materials illuminates the progressive filtering downward of complex mathematics to younger and younger students (Fig. 5). At the end of the 19th century, secondary and post-secondary mathematics instructors viewed geometry as one of the crowning content areas, and hence, a subject reserved only for college coursework or for upper level students in high schools or private academies. Panel 5a provides a representative geometry problem that would have been saved for mathematics students far along in their studies. Indeed, even for advanced students it was rare to be given the opportunity to integrate plane and solid geometry; the example in Panel 5a asks advanced secondary students to engage in a visual-spatial working memory task that requires visualization of the transition between two- and three-dimensional objects.

By the middle of the 20th century, curriculum developers introduced similar geometry problems at the early high school and junior high school level. Panel 5b presents a problem from a 1955 seventh-grade textbook that requires the student to focus on volume, squares, and cubes in much the same way as had previously been introduced to much older students. By the 1970s, as shown in Panel 5c, two- and three-dimensional problems could be found in most third-grade textbooks. By the early 1990s, much of the basic conceptual work of geometry was delivered to children in kindergarten, first, and second grade (Panel 5d). Currently, young children regularly engage in visual-spatial problem solving associated with

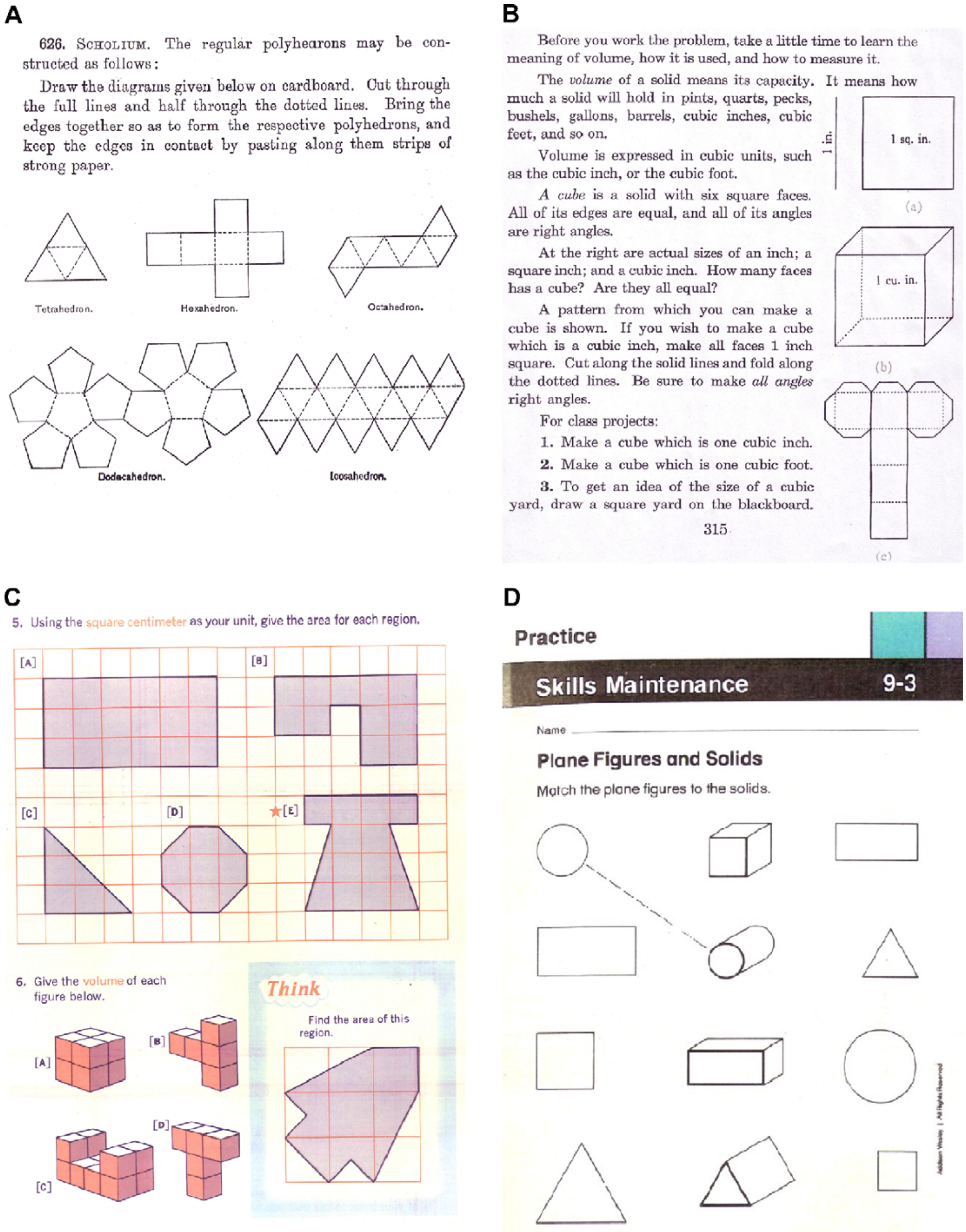


Fig. 5. The "push down" of geometry problems.

prefrontally based working memory functions that their grandparents' generation would not have been exposed to until the seventh or eighth grade and that their great-grandparents' generation may not have been introduced to at all.

5. Neurodevelopmental-schooling hypothesis and changes in population fluid skills

Coupled with increased school enrollments early in the 20th century, the historical change in mathematics education for young children, particularly from the 1950s on, suggests a plausible hypothesis that *prima facie* meets the requirements of an explanation for rising mean IQ in the population. Although it is widely recognized that the change in measured IQ has occurred far too rapidly to be attributable to genetic selection, the search for an environmental mechanism has been stymied by the fact that intelligence shows high heritability. However, as demonstrated by Dickens and Flynn (2001, 2002), the assumption of large environmentally driven gains in intelligence can be reconciled with the assumption of high heritability for intelligence. This is because the occurrence of gene-environment correlation resulting from reciprocal causation between phenotypic IQ and environment can mask the potency of the effect of the environment on intelligence.

Most importantly, reciprocal causation has been demonstrated within a formal model to produce a multiplier effect within which the size of the requisite environmental influence on intelligence can be quite small but still produce a considerable environmentally driven increase (Dickens & Flynn, 2001). For example, if genes and environments are uncorrelated and the average heritability of IQ is around 0.75, any environmental change required to bring about a two standard deviation increase in intelligence would have to be enormous. However, mathematical modeling of the multiplier effect indicates that the environmental trigger that spurs environmentally driven changes in IQ can be of modest size. This is particularly true if variance in exposure to that trigger is relatively small, if the likelihood of exposure to that trigger is only weakly correlated with genetic endowment for IQ, and if the exposure begins early in the lifespan, all factors which align with the neurodevelopmental-schooling hypothesis.

Although prior attempts to explain the phenomenon of rising mean IQ have suggested general changes in experience (e.g., general increases in education, parenting skill, or nutrition), no explanation to date has proposed a central mechanism that directly addresses the predominance of gains in fluid skills, and none has proposed a mechanism that possesses the specific characteristics of exposure required by the multiplier effect. Specifically, three facts highly recommend changes in math education as a likely environmental trigger for rising mean IQ: (1) changes in mass enrollment in schooling and in mathematics curricula were both widespread; (2) these organizational factors are uncorrelated with genetic endowment for intelligence (particularly so over the century); and, (3) changes in math instruction promoting fluid skills are most pronounced in the early elementary grades.

6. Discussion

Explaining the substantial rise in mean IQ over the past century represents a significant challenge to our understanding of intelligence and how it develops across human populations. Prior attempts to develop environmental explanations for rising mean IQ have lacked specificity as to plausible causal mechanisms that would account for population-wide growth in fluid performance over historical time (see Flynn, 1998). Although speculative, like all explanations for rising mean IQ, the neurodevelopmental-schooling hypothesis meets essential criteria for an environmental explanation for the phenomenon. This hypothesis is supported by the historical spread of schooling and the increasing intensification of mathematics curricula over the 20th century, suggesting that cognitive developmental processes are interrelated with, and mediated by, educational practice at a given point in time.

Importantly, and in alignment with Flynn (1999, in press), we suggest that increasing mean IQ represents an increase in aspects of mental ability that correlate with performance on measures of IQ. Functional implications of these gains for real world competence, however, remain unclear, particularly given the paradoxical finding that increasing fluid cognitive demand of early elementary math education has not led to substantial increased math achievement over time.

Several directions for future research are indicated, however, that could help to resolve issues related to the neurodevelopmental-schooling hypothesis and place it on firmer empirical ground. At least four types of studies are recommended. The first type would fully document and test the idea that over the course of the 20th century the American mathematics curriculum in the early elementary grades increasingly came to focus less on rote memorization of mathematic facts and more on categorization, pattern recognition, and intuitive geometry, including the grouping of numbers, approximating values, the identification of geometric configurations, visualization through the manipulation of three-dimensional objects, and physical interpretation of fractions. A useful extension of this research would be to test this claim in the historical development of mathematics curricula in other nations where fluid IQ increases in the population have also been observed (Flynn, in press).

A second type of study would utilize functional magnetic resonance imaging to determine whether representative problem types from late versus early time points in the historical development of mathematics curricula in American schools over the 20th century are associated with greater activations in areas of the prefrontal cortex known to be associated with fluid cognition. Such studies would provide evidence of the increasing fluid cognitive demand of changes in math curricula and suggest that repeated exposure to problem types that require fluid skills are exercising specific areas of the brain known to be associated with fluid intelligence. The same method would also test if the performing of more routine algorithm based procedures is associated with less prefrontal activity.

Similarly, a third type of study would test the relationship between young students' performance on neuropsychological measures of fluid cognition, standardized math achievement, and performance of math tasks that are judged to be high in fluid cognitive skills. This type of study would help to address the discrepancy in which problem types that are high in fluid cognitive content may be positively associated with higher levels of reasoning ability but not math achievement. This type of study could also develop and test an expanded notion of schooling effects on fluid IQ enhancement by including variation in exposure to schooling, curricular content, and instructional emphasis of various curricula (Williams, 1998).

And finally, a fourth type of related study would utilize a randomized experimental training framework to examine the extent to which intensive training on the problem types associated with fluid cognitive skills that have increased as a proportion of the early elementary math curriculum in the US are associated with changes in fluid intelligence. This type of study would provide perhaps the strongest inference about the relation between curriculum change and rising mean IQ. In fact, preliminary evidence from two studies indicate that training on fluid cognitive processes leads to increases in test scores on measures of fluid intelligence such as the Raven's test. In a randomized, controlled design, children with ADHD who received a computer-based fluid skills training program for 20 min per day, 4–6 days per week over a 5-week period were found to exhibit greater working memory and increased Raven's scores relative to a group receiving a control program (Klingberg, Forssberg, & Westerberg, 2002). A within-person replication of the training results with four typically developing adults also indicated posttest gains on the Raven's associated with the fluid skills training program (Klingberg et al., 2002). Similarly, a computer-based training program designed to promote attention shifting and executive attention in which typically developing 4-year-olds received five 1-h sessions over a week's time was also found to increase fluid but not crystallized intelligence as assessed by the Kaufman Brief Intelligence Test relative to a group receiving a control program (Posner, Rothbart, & Rueda, 2004; Posner & Rothbart, in press). Although, only two preliminary studies, results from these training programs strongly suggest the possibility that repeated practice with problem-types that draw on fluid cognitive skills may be associated with the well-documented long-term population increase in specific aspects of measured intelligence.

References

Benes, F. M. (2001). The development of prefrontal cortex: The maturation of neurotransmitter systems and their interactions. In C. Nelson, & M. Luciana (Eds.), *Handbook of developmental cognitive neuroscience* (pp. 79–92). Cambridge: MIT Press.

Bourgeois, J. P., Goldman-Rakic, P. S., & Rakic, P. (1994). Synaptogenesis in the prefrontal cortex of Rhesus monkeys. *Cerebral Cortex*, *4*, 78–96.

Braver, T. S., Cohen, J. D., Nystrom, L. E., Jonides, J., Smith, E. E., & Noll, D. C. (1997). A parametric study of prefrontal cortex involvement in human working memory. *Neuroimage*, *5*, 49–62.

Bull, R., & Scerif, G. (2001). Executive functioning as a predictor of children's mathematics ability: Inhibition, switching, and working memory. *Developmental Neuropsychology*, *19*, 273–293.

Campbell, J. R., Hombo, C. M., Mazzeo, J., & National Center for Education Statistics (2000). *NAEP 1999 trends in academic progress: Three decades of student performance*. Washington, DC: U.S. Dept. of Education Office of Educational Research and Improvement.

Carpenter, P. A., Just, M. A., & Shell, P. (1990). What one intelligence test measures: A theoretical account of the processing in the Raven Progressive Matrices Test. *Psychological Review*, *97*, 404–431.

Ceci, S. (1991). How much does schooling influence general intelligence and its cognitive components? A reassessment of the evidence. *Developmental Psychology*, *27*(5), 703–722.

Ceci, S. J., & Williams, W. M. (1997). Schooling, intelligence, and income. *American Psychologist*, *52*, 1051–1058.

Clason, R. G. (1968). *Number concepts in arithmetic texts of the United States from 1880 to 1966, with related psychological and mathematical developments*. Unpublished Doctoral, University of Michigan, Ann Arbor.

Dickens, W. T., & Flynn, J. R. (2001). Heritability estimates versus large environmental effects: The IQ paradox resolved. *Psychological Review*, *108*, 346–369.

Dickens, W. T., & Flynn, J. R. (2002). The IQ paradox is still resolved: Reply to Lochlin and Rowe and Rodgers. *Psychological Review*, *109*, 764–771.

Duncan, J., Burgess, P., & Emslie, H. (1995). Fluid intelligence after frontal lobe lesions. *Neuropsychologia*, *33*, 261–268.

Duncan, J., Seitz, R. J., Kolodny, J., Bor, D., Herzog, H., Ahmed, A., et al. (2000). A neural basis for general intelligence. *Science*, *289*, 457–460.

Embretson, S. (1995). The role of working memory capacity and general control processing in intelligence. *Intelligence*, *20*, 169–189.

Evans, J., Floyd, R., McGrew, K. S., & LeForgee, M. (2002). The relations between measures of Cattel-Horne-Carroll (CHC) cognitive abilities and reading achievement during childhood and adolescence. *School Psychology Review*, *31*(2), 246.

Flynn, J. R. (1984). The mean IQ of Americans: Massive gains 1932 to 1978. *Psychological Bulletin*, *99*, 29–51.

Flynn, J. R. (1987). Massive IQ gains in 14 nations: What IQ tests reallly measure. *Psychological Bulletin*, *101*, 171–191.

Flynn, J. R. (1998). IQ gains over time: Toward finding the causes. In U. Neisser (Ed.), *The rising curve: Long term gains in IQ and related measures* (pp. 25–66). Washington, DC: American Psychological Association.

Flynn, J. R. (1999). Searching for justice: The discovery of IQ gains over time. *American Psychologist*, *54*, 5–20.

Goldman-Rakic, P. S., Bourgeois, J. -P., & Rakic, P. (1997). Synaptic substrate of cognitive development: Lifespan analysis of synaptogenesis in the prefrontal cortex of the nonhuman primate. In N. Krasnegor, R. Lyon, & P. Goldman-Rakic (Eds.), *Development of the prefrontal cortex: Evolution, neurobiology, and behavior* (pp. 27–47). Balitmore, MD: Brookes.

Gray, J. R., Chabris, C. F., & Braver, T. S. (2003). Neural mechanisms of general fluid intelligence. *Nature Neuroscience*, *6*, 316–322.

Grissmer, D. W. (2000). The continuing use and misuse of SAT scores. *Psychology, Public Policy, and Law*, *6*, 223–232.

Grissmer, D. W., Williamson, S., Kirby, S. N., & Berends, M. (1998). Exploring the rapid rise in Black achievement scores in the United States (1970–1990). In U. Neisser (Ed.), *The rising curve: Long term gains in IQ and related measures* (pp. 251–285). Washington, DC: American Psychological Association.

Gustafsson, J. -E. (1984). A unifying model for the structure of intellectual abilities. *Intelligence*, *8*, 179–203.

Jensen, A.R. (1998). The g factor: The science of mental ability. Westport CT: Praeger.

Kazui, H., Kitagaki, H., & Mori, E. (2000). Cortical activation during retrieval of arithmetical facts and actual calculation: A functional magnetic resonance imaging study. *Psychiatry and Clinical Neurosciences*, *54*, 479–485.

Klingberg, T., Forssberg, H., & Westerberg, H. (2002). Training of working memory in children with ADHD. *Journal of Clinical and Experimental Neuropsychology*, *24*, 781–791.

Kyllonen, P. C. (1996). Is working memory capacity Spearman's g? In I. Dennis, & P. Tapsfield (Eds.), *Human abilities: Their nature and measurement* (pp. 49–76). Mahwah, NJ: Erlbaum.

McGrew, K. S., & Hessler, G. L. (1995). The relationship between the WJ-R GF-GC cognitive clusters and mathematics achievement across the life span. *Journal of Psychoeducational Assessment*, *13*, 21–38.

McLean, J. F., & Hitch, G. J. (1999). Working memory impairments in children with specific arithmetic learning difficulties. *Journal of Experimental Child Psychology*, *74*, 240–260.

National Council of Teachers of Mathematics (1970). *A history of mathematics education in the United States and Canada*. Washington, DC: Author.

Nicely, R. F. (1991, Summer). Higher-order thinking skills in mathematics textbooks: A research summary. *Education*, *CXI*(4), 456–460.

Plomin, R., DeFries, J., McLearn, G., & Rutter, M. (1997). *Behavioral genetics* (3rd ed.). New York: Freeman.

Posner, M., & Rothbart, M. (2004). *Educating the human brain*. In press.

Posner, M., Rothbart, M., Rueda, R. (2004, February). *Developing self-regulation in preschool children*. Paper presented at the annual meeting of the American Association for the Advancement of Science, Seattle Washington.

Prabhakaran, V., Smith, J. A. L., Desmond, J. E., Glover, G. H., & Gabrieli, J. D. E. (1997). Neural substrates of fluid reasoning: An fRMI study of neocortical activation during performance of the Raven's Progressive Matrices Test. *Cognitive Psychology*, *33*, 43–63.

Prabhakaran, V., Narayanan, K., Zhao, Z., & Gabrieli, J. D. E. (2000). Integration of diverse information in working memory within the frontal lobe. *Nature Neuroscience*, *3*, 85–90.

Prabhakaran, V., Rypma, B., & Gabrieli, J. D. E. (2001). Neural substrates of mathematical reasoning: A functional magnetic resonance imaging study of neocortical activation during performance of the necessary arithmetic operations test. *Neuropsychology*, *15*, 115–127.

Ramey, C. T., & Campbell, F. A. (1984). Preventive education for high-risk children: Cognitive consequences of the Carolina Abecedarian Project. *American Journal of Mental Deficiency*, *88*, 515–523.

Rice, J. M. (1893). *The public school system of the United States*. New York: Century Press.

Rubinson, R., & Fuller, B. (1992). Specifying the effects of education on national economic growth. In B. Fuller, & R. Rubinson (Eds.), *The political construction of education* (pp. 101–115). New York: Praeger.

Semendeferi, K., Lu, A., Schenker, N., & Damasio, H. (2002). Humans and great apes share a large frontal cortex. *Nature Neuroscience*, *5*, 272–276.

Waltz, J. A., Knowlton, B. J., Holyoak, K. J., Boone, K. B., Mishkin, F. S., Santos, M., et al. (1999). A system for relation reasoning in the human prefrontal cortex. *Psychological Science*, *10*, 119–125.

Wicherts, J., Dolan, C., Hessen, D., Oosterveld, P., van Baal, C., Boomsma, D., & Span, M. (in press). Are intelligence tests measurement invariant over time? Investigating the nature of the Flynn effect. *Intelligence*, *32*, 509–537.

Williams, W. M. (1998). Are we raising smarter children today? School-and home-related influences on IQ. In U. Neisser (Ed.), *The rising curve: Long term gains in IQ and related measures* (pp. 125–154). Washington, DC: American Psychological Association.