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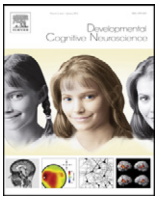

An envisioned bridge: Schooling as a neurocognitive developmental institution

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ABSTRACT

The potential contribution of social science research to close the gap of knowledge between cognitive neuroscience and educational research has been underappreciated. Despite their virtual absence in the interdisciplinary dialog of neuroscience, sociology of education and related study of the cultural impact of formal education have generated research relevant to an understanding of how the social environment, such as widespread schooling, co-evolves with, and enhances neurocognitive development. Two clusters of isolated research literatures are synthesized that taken together anticipates a dynamic integration of neuroscience and education. The first cluster is on the social construction of cognition through formal education in contemporary society, including the effects of schooling on neurological and cognitive development; the demographic expansion of exposure to the developmental influence of schooling; and education's cultural impact on the meaning of the learning experience and reinforcement of cognition as the key human capability across ever more key institutions in postindustrial society. The second cluster turns the issue around by examining current investigations from neuroscience that support neurological hypotheses about the causes behind the schooling effect on neurocognitive development. We propose that further integration of these literatures will provide a more ecologically valid context in which to investigate the evolving functional architecture of the contemporary brain.

In his seminal perspective published in Educational Researcher in 1997 ("Education and the Brain: A Bridge Too Far"), Breuer cogently argued that, despite some early optimistic claims, the chasm between neuroscience and education was too great to be easily bridged in any meaningful way. For over a decade, this appraisal significantly deflated the expectation among the educational establishment about the contributions of the cognitive and neural sciences to formal schooling. Much neuroscience and cognitive research, as well as social science and theory applied to education has occurred since, and in many ways Bruer's "bridge too far" may now be coming into clearer focus. We contend that implications of a set of central findings from developmental neuroscience in conjunction with renewed sociological analyses of cognition and of schooling as a developmental environment indicate that the coming bridge will likely be dynamic and interactive (De Smedt et al., 2009; Mayer, 1998).

Two clusters of research are synthesized that have until now been isolated from one another, yet taken together

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anticipates a dynamic integration of neuroscience and education. In one cluster are three related research literatures on the main sociological processes involved in the social construction of cognition through education in contemporary society. Evidence on this includes: first, research findings on the effects of schooling on neurological and cognitive development; second, the demographic expansion of exposure to the developmental influence of schooling through the phenomenon of the 'educational revolution' over the 20th century; and third, indications of institutional and cultural changes that affect the meaning of the learning experience and reinforce cognition as key human capability across ever more key institutions in postindustrial society. The second cluster of research turns the issue around by hypothesizing that current investigation from neuroscience support neurological causes behind the schooling effect on neurocognitive development. Even though human cognitive development is robust in the face of many biological and environmental hazards, cultural and other environmental exposures mediate variables that modify brain structure and function, and schooling is one such environment. Evidence to support this hypothesis is drawn from first, findings about the fundamental role of neural plasticity in skill learning and adaptive human behavior; second, the neurological effects of schooling as revealed in samples of literate versus illiterate adults; and third, the expanding reach of research on learning effects and the brain in typically-developing school children and adolescents.

1. Formal education as a neurocognitive-developmental institution

Considerable evidence indicates an effect of schooling on neurocognitive development; and this effect is likely intensely reinforced by several powerful sociological processes that give formal education and cognition deep meaning in contemporary society.

1.1. Schooling effects on neurological and cognitive development

An often underappreciated set of findings reported on and off over the past 70 years points to the possibility that what occurs in school has an influence on neurocognitive development, irrespective of the specific content area taught. This seems especially true for executive functions that provide domain-general resources for planning, organization, working memory and integration of experience, knowledge and skills for goal-directed behaviors. This has sometimes been referred to as *g*, or the general factor underlying intelligence and cognitive capacities, as posited by Spearman (1923) and more recently redefined by Duncan et al. (1996) in terms of executive control functions. Hence, this construct views such cognition as involving shared resources that are applicable across multiple specific content areas and situations. This body of findings has led to the same conclusion: Learning basic literacy, numeracy, and other academic subjects, even under rudimentary conditions for only a few years of schooling, leads to a number of cognitive enhancements that cause schooled individuals, *ceteris paribus*, to think and reason in a fashion significantly different from unschooled individuals. So too, there is evidence that working memory, inhibitory control, and attention-shifting processes, as well as components of decision making and novel problem solving are enhanced by exposure to formal education (Nisbett, 2009; Ardila et al., 2010). Certainly children enter school with differing levels of genetically endowed potential for intelligence and differing influences of early parenting. However, whatever these entrance characteristics, they are immersed in a structured curriculum and sustained learning environment that prioritizes cognitive abilities. Reading, writing, and understanding numbers and basic operations are themselves a transforming set of skills, but there is evidence that in the process of learning these skills, the scope and depth of cognition and components of executive functioning are enhanced as well.

Perhaps most convincing are quasi-experimental studies of unschooled and schooled adults in subsistence-level farming communities that find even small amounts of schooling as a child yield higher-order cognitive skills among adults after controlling for work conditions and more general social and economic status (Christian et al., 2001; Cole, 1996; Luria, 1976; Stevenson and Chuansheng, 1989; Stevenson et al., 1990). For example, starting in the 1930s, when large numbers of unschooled Russian peasants lived alongside those who had had access to some schooling as children, Vygotsky (1978) and colleague Luria reported evidence of differences in thinking styles between unschooled and schooled adults. Adults with some exposure to formal school showed greater propensity to use cognitive abstraction and reasoning to solve new problems, while unschooled adults tended to rely on their concrete experiences even at the perceived risk of finding an incorrect solution. Since this initial finding, the impact of schooling on the ability to reason more abstractly and solve problems more flexibly in new and unique situations have been demonstrated in related research in other cultures as mass schooling was introduced (Cole, 1996; Stevenson and Chuansheng, 1989; Stevenson et al., 1990; Tulviste, 1991a,b; Diamond and Lee, 2011).

Similarly, American research from the first half of the 20th Century, before full enrollment in mass education, showed schooling's influence on children's general cognitive abilities beyond specific skills and factual knowledge. A meta-analysis of over fifty early studies using naturalistic observation, post hoc statistical comparisons, and cohort-sequential analysis concluded that there is a stable and robust association between schooling and the enhancement of cognitive skills (Ceci, 1991). Estimating across the studies, schooling enhanced various measures of IQ by .3–.6 of a point for every year of exposure so that even a modest school career yields enhancement.[1] Importantly, the association between IQ and exposure to formal education is not due to high aptitude children staying in school longer (i.e. selection effects). Instead, by comparing children similar on

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[1] With a standard deviation of 15 points, a half point increase for each school year match the size of population IQ score gains found across successive cohorts of test-takers, known as the Flynn Effect described below.

family social background and initial intelligence but with different exposures to schooling, these studies support a non-spurious statistical association between schooling and cognition. Along this line, comparing students' academic gains over the school year versus the summer vacation when many have little contact with schooling, Downey et al. (2004) report a significant drop during the summer controlling for a host of other social and material conditions of students and their families. And a recent study of statistical estimates obtained from analysis of continuous variation in age and length of formal education finds that exposure to schooling is associated with IQ increases three to four times that from maturation (Cliffordson & Gustafsson, 2008).

Advances in instrumentation for measuring cognition and experiments with functional MRI enable a detailed analysis of schooling effects on neurocognitive development as reported in three new studies, and in an additional recent set of research findings.

First, a naturally-occurring experiment among Ghanaian subsistence-level famers who as children experienced different levels of modest schooling (mean of 6.6 years, including no schooling) measured components of executive functioning and higher-order cognition including: working memory (backward-digit task, Wechsler, 1981); planning, strategy, working-memory, and attention-shifting abilities (The Delis-Kaplan Executive-Function System Tower; Delis et al., 2004), numeracy (Woodcock-Johnson-III-Calculation); and, decision-making ability (a culturally-adapted ratio-bias task, Stickman Task, Peters et al., 2006). Since the original study analyzed how cognitive enhancement mediates the influence of schooling on understanding and enacting protective behaviors against HIV/AIDS infection, Fig. 1 presents a re-estimated structural equation model of just the influence of exposure to schooling on cognitive enhancement (Peters et al., 2011). As shown, there is a medium-sized effect of schooling: A one standard deviation increase in exposure to schooling as a child is associated with an increase of .61 of a standard deviation in executive functioning and cognitive abilities as an adult, controlling for gender, age, and socio-economic status (which has limited variation in this population).

Second, a unpublished replication of this naturally-occurring experiment in the different cultural setting of Peruvian Andean rural villages estimated the same structural equation model as in Fig. 1 above, but with the addition of controlling on crystallized IQ (Peabody Picture Vocabulary Test). Results indicate a similar significant association between schooling and executive functioning and cognitive abilities. Also the estimated effect of schooling on executive functioning and cognitive abilities in both studies remained substantial and statistically significant after introduction of controls for sample-selection bias and endogeneity – correlated, unobserved factors relegated to the error terms – which in both cases were found to be minimal.

Generalizability of the schooling effect on cognitive development is demonstrated by a third study that estimated a model similar to the one described above with data from large, nationally representative, probability samples of the Demographic Health Survey from nine sub-Saharan African nations (combined $N = 19{,}800$) (Baker et al., 2010b). With large variation in exposure to schooling among adults, including unschooled and those with only a few years of primary schooling, a robust effect of education on higher order reasoning about causes of HIV infection was found, after statistical conditioning on a range of socio-economic and demographic characteristics of subjects plus a Heckman (1979) self-selection probability to control for potential selection bias.[2] Although the measures of reasoning in these data are indirect, given the nature of the samples, the results indicate a significant level of generalizability of the education effect.

Fourth, neurocognitive and neuroimaging studies show an increasingly strong association between the learning experience in classrooms and identifiable adaptive changes in the brain. For example, in a well-controlled set of studies, Castro-Caldas and colleagues have demonstrated that healthy adults who were never exposed to formal schooling for social reasons encountered significantly greater difficulties in parsing and repeating pseudowords, tending to transform pseudowords into words. This difference was reflected in their lack of metabolic brain activation in several regions characteristic of literate adults (Castro-Caldas et al., 1998). Structural differences have also been identified in the volume of the corpus callosum, the main pathways connecting the cerebral hemispheres, particularly where parietal lobe fibers cross (Castro-Caldas et al., 1999). In addition, numerous and far-reaching neuropsychological differences have been identified, with lower scores associated with lack of formal schooling (see Ardila et al., 2010 for review). However, exposure to even 1–2 years of formal schooling is enough to significantly distinguish adults on measures of language comprehension, phonological verbal fluency, and verbal abstract reasoning (Ostrosky et al., 1998).

1.2. The education revolution and societal intensification of schooling

There have been two major effects of the education revolution on the making of schooling into a neurocognitive developmental institution. The first is that the micro-effects of schooling on neurocognitive development now reach most children and youth because of the phenomenon known as the education revolution, which sociological research has shown to be one of the most striking and transformative social processes of our age (e.g. Arum and Beattie, 2000; Baker, 2011a; Meyer, 1977; Parsons, 1971). The education revolution has led to unprecedented exposure across the human population to a relatively similar environment of formal education that is supported by intensifying social significance of educational attainment in postindustrial society.

Gross enrollment rates have risen consistently over the past 150 years, justified as preparing all children for the adult world. Near full enrollments have been attained in

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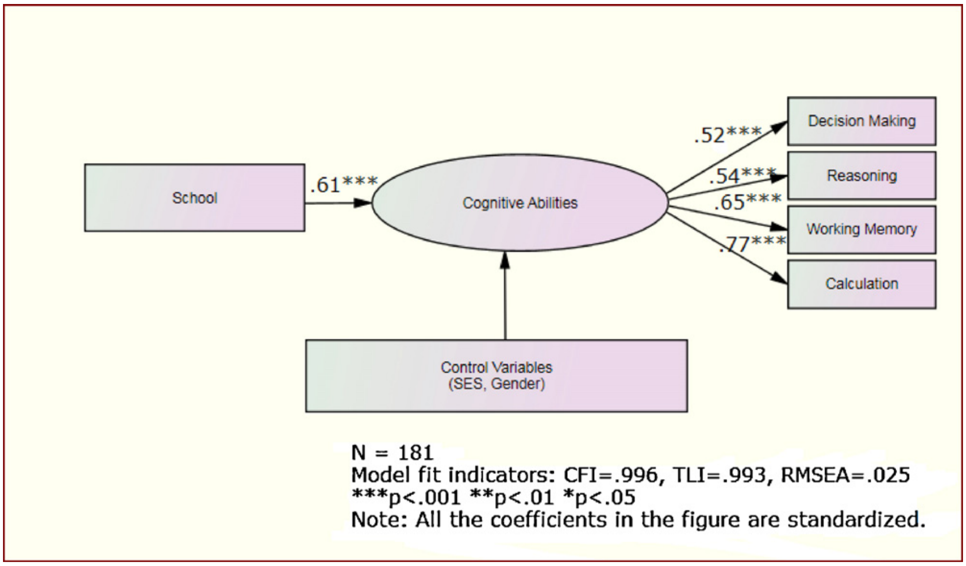
[2] The informally termed "Heckman correction" is a standard econometric procedure used to control for the probability of self-selection into the sample. For further information, see Heckman (1979).



N = 181
Model fit indicators: CFI=.996, TLI=.993, RMSEA=.025
***p<.001 **p<.01 *p<.05
Note: All the coefficients in the figure are standardized.

Fig. 1. Structural equation model of relationship between exposure to school and adult executive functioning and cognitive abilities among rural Ghanaians.

primary school, first in wealthier nations, and since the middle of the twentieth century, have spread globally (Benavot and Riddle, 1988; Fuller and Rubinson, 1992). Consequently, 80% of all persons age 15 or older worldwide are able to both read and write a short statement about their life; a phenomenon that would have been hard to imagine fifty years ago (UNESCO, 2002).[3] Along with the diffusion of mass education, the normative standard of educational attainment has risen with each new generation of schooled parents. For example, the United States has led the way in developing mass education; a hundred years ago about one-half of all US school-aged children were enrolled in school, whereas the proportion rose to 75% within the next forty years and to almost 90 percent over the next twenty years. Not stopping at primary and secondary education, the education revolution has ushered in mass higher education enrollments. At the turn of the 19th century less than 1% of university-aged youth across the world attended, now 20% or approximately 100 million attend some kind of higher education (Schofer and Meyer, 2005).

Also the core values and social meanings behind education have become remarkably similar worldwide; so much so that there is an increasing trend among nations to employ a similar model of formal education from the earliest grades up through graduate study at the university. This global institutional similarity or ‘isomorphism’ happens despite moderate variation in performance or outcomes of educational systems over the world (Baker and LeTendre, 2005; DiMaggio and Powel, 1983). And demand for formal education often runs ahead of supply, as evidenced by the fact that even among the poorest of people, after basic nutrition and health needs are met, parents demand education for their children as the central way to help them achieve a better life (UNESCO, 2002).

This expansion is accompanied by growing commitments of individuals and families and societal investments in schooling. For example, as in other developed nations the length of the American school year grew from about six and one half months just before the beginning of the 20th century to its current nine months of schooling, representing an estimated 50% increase in instruction time (US Department of Education, 1993). Also as the average student/teacher ratio declines, one can assume that the resources and intensity of education are increasing, and this ratio has fallen steadily from the end middle of the 19th century so that by 2007 nationwide there were an estimated mean of 15.4 public school pupils per teacher (US Dept. of Education, NCES 2008). In constant 1990 dollars, the average total expenditure on a public school student grew from only $355 in 1919 to an average of $9518 for every student in fiscal year 2004 (US Dept. of Education, 1993).[4]

The second major effect brought on by the education revolution is the central role schooling plays in society. Five decades of sociological research shows the inexorable movement away from non-educational factors influencing individuals’ ultimate social status to a society where education performance singularly dominants social status attainment. Early systematic investigation of social mobility shows that across populations a century and one half ago, formal education played only a minor role in the process of intergenerational mobility. Instead, a variety of non-educational allocation mechanisms and criteria dominated intergenerational social mobility in preindustrial and early industrialization societies, such as family origin,

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[3] Most people who are still illiterate are living in very poor nations and seven out of ten are women (UNESCO, 2002).

[4] While there is variation across American school districts in expenditures and resources, these indicators represent long-term historical trends that generally apply nationwide and internationally too.

position in a social stratum, status inheritance, sinecure, marriage, age, gender, religious charisma, guild training, patronage, caste, and land ownership (Collins, 1979). This changed rapidly over the course of the education revolution (Baker, 2011b).

By the 1960s in the US and other nations with developed primary and secondary school systems, statistical modeling of large samples of longitudinal demographic data revealed that educational attainment early in life had become one main predictive factor of eventual adult social status to a level never before seen in human society (e.g. Blau and Duncan, 1967). And contrary to expectations held before this research, education was found to play two roles once thought to be mutually exclusive—education had become central to intergenerational social status reproduction *and* the achievement of status (Hout and DiPrete, 2006). In other words, while educational attainment had become the main route to an individual's adult status, educational attainment was influenced by both social origins (i.e., parents' socioeconomic status—SES) and factors independent of social origins (i.e., success or failure at schooling due to effort, intelligence, and motivation), supporting a significant cultural focus of formal schooling on cognitive activities related to learning. This shift was a substantial one, the direct influence of social origin on the adult child's status was now remarkably modest and most effect moved through the offspring's education attainment, so that, over just several generations, education had thoroughly saturated intergenerational social mobility in the US and other heavily schooled nations (e.g. Breen and Luijkx, 2007; Hout, 1988; Ishida, 1993; Shavit and Blossfeld, 1993; Treiman and Ganzeboom, 1990).

In the late 1980s, research found that parental social origin still influenced the child's education attainment, but the strength of this relationship had declined by a full third from what it had been in the 1960s (Hout, 1988). Furthermore, the relationship was disconnected completely among offspring completing a college degree. In other words, evidence showed that educational achievement of the individual had an independent and dominating effect on status attainment across the full population. Torche (2010) and Brand and Xie (2010) replicate these American findings, which have also been reported in studies from Sweden, France and Germany (Vallet, 2004; Breen and Jonsson, 2007; Breen and Luijkx, 2007).

In a sociological sense, attending school for a considerable number of years is a new and large-scale change in the typical socio-cultural environment and behavior of children and youth, as well as in the organization and priorities of their families and communities without parallel in pre-modern, traditional human society. In a neurocognitive developmental sense, by making exposure to increasing amounts of schooling a normative life-course event and touting the importance of educational achievement, the education revolution has for the first time in human history spread a distinctively cognitively rich developmental environment. Further, the fact that academic performance has become the major mechanism to attain adult status generates significant motivation on the part of parents and students to intensely participate in this environment and deeply legitimates the institution of education and furthers its expanding culture of cognition.

1.3. *The education culture and cognition as a key human capability*

If it is true that the education revolution has nurtured and distributed a demanding and sustained neurocognitive developmental environment in burgeoning proportions of children, then there should be evidence of widespread cognitive enhancements and their effects at the population level. There should also be evidence of influence of mass education's culture of cognition on other social institutions. Three sets of empirical findings indicate these kinds of effects have occurred.

First is the evidence supporting a three-part hypothesis that the education revolution is a probable chief cause of historical improvements in population health, and the key causal mechanism is widely spread enhanced cognitive skill. The first part is the large volume of research reporting that educational attainment is the single best demographic predictor of *positive health outcomes* across individuals, even after controlling for social and material benefits gained from educational degrees and occupation; see, for example, Mirowsky and Ross' (2003) extensive review of education's association with all types of health outcomes, and Baker et al.'s (2011) meta-analysis of education effects on all-cause mortality. A typical study is Backlund et al.'s (1999) longitudinal analysis of 400,000 Americans that finds after statistically conditioning on a host of demographic factors, women and men with primary education or less were respectively 33% and 42% more likely to have died before more educated individuals; and, in a study with more recent data Brown et al. (in press) find that what had been a linear downward slope between education and risk of death turns sharply downward among the population with a college degree or higher. Second, there is evidence that education's impact on domain general intelligence is a key causal factor in individuals' health, fertility (and their child's health), and longevity. Starting with Gottfredson's (1997) argument about intelligence's implications for everyday life, recent epidemiological research confirmed an association between intelligence, as measured on standard IQ instruments, and health outcomes (e.g. Batty et al., 2007; Gale et al., 2010). And third is a growing set of research on health outcomes showing that school enhanced cognition significantly mediates the association between educational attainment and health and longevity (e.g. Baker et al., 2010b, 2011; Herd, 2010; Peters et al., 2011).

This mass education-population health hypothesis has been applied to research about the first demographic transition (hereafter, FDT), a foundational health transformation of the population reflected in extensive decline in crude death rates and crude birth rates among populations in Western Europe and North America beginning in the 19th century. Since a number of earlier hypotheses about economic development, medical technologies, and nutritional improvements as the causes of the FDT were disproved, the spread of mass schooling is now the leading causal hypothesis of this demographic shift

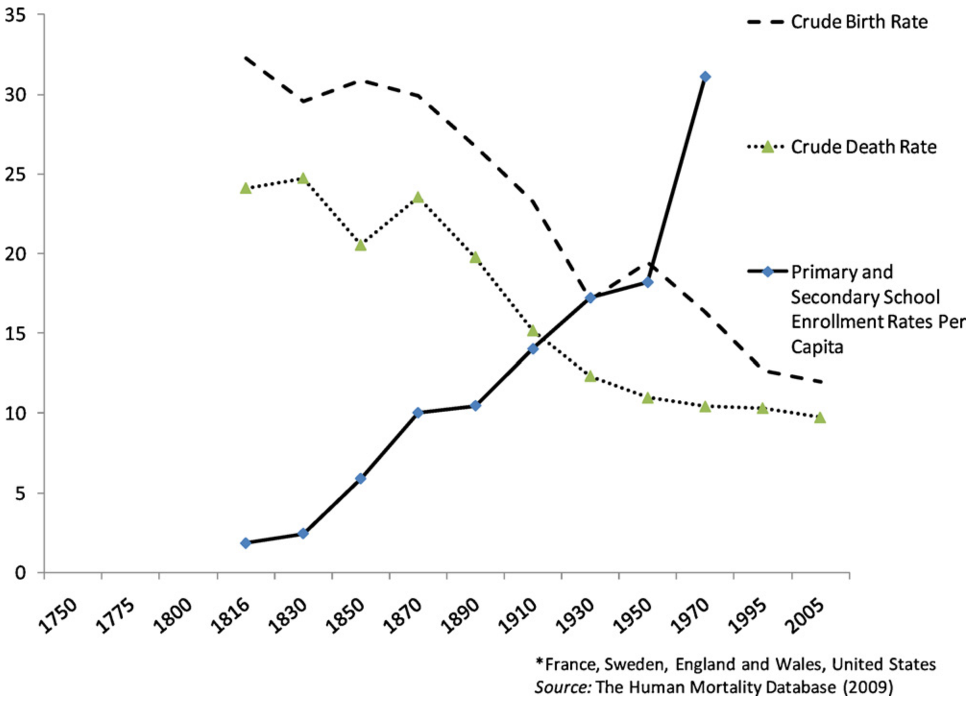

Fig. 2. Timing of the onset of the first demographic transition and the educational revolution in England and Wales, France, Sweden, and the United States. From Baker et al. (2011).

and subsequent demographic transitions in less developed nations over the 20th Century (Baker et al., 2011; Caldwell, 2006; Hobsbawn, 1983; Le Fanu, 1999). As shown in Fig. 2, the timing of the FDT and the take off of the education revolution in these nations is compatible with the mass education-population health hypothesis.

The second consequence is the evidence that the education revolution is closely associated with the Flynn effect, which refers to the rapid and progressive rise in mean level IQ in national populations in North America, Western Europe, and Japan across the 20th century. This rise across birth cohorts of adults has been particularly evident from performance on the Raven's Progressive Matrices Test, a measure of reasoning ability as applied in novel contexts and an indicator of fluid IQ (e.g. Flynn, 1984, 1987).[5] 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. When initially recognized as a valid trend, a number of causal hypothesis were put forth, but these have since failed to meet all three necessary logical propositions to be a causal factor of this historical trend (Neisser, 1998). So far, the hypothesis that formal education is an identifiable contributor to the Flynn effect has met all three (Blair et al., 2005). The first proposition, that an environmental cause of population increase in fluid IQ must be clearly associated with significant gains in fluid cognitive skills, is evidenced by the above reviewed research on schooling effects lasting into adulthood. The second proposition is that increasing numbers of individuals within cohorts must have been exposed to the hypothesized cause matching the monotonic increase in population fluid IQ. This proposition is met by the fact that by the early 20th century a significant proportion of children in nations experiencing the Flynn effect were exposed to schooling and there has been a linear increase in average years of attainment across cohorts ever since. The third proposition relates to the homogenization and intensification of a causal factor. The evidence on the former, that within cohorts there must be exposure to a relatively uniform causal mechanism (i.e., mass schooling), has been reviewed and confirmed above. The latter, that as full exposure occurs across cohorts there must be evidence of historical intensification of the causal mechanism, may seem to rule out a mass schooling hypothesis because it is often assumed that the curriculum of schooling has been slowly "dumbed down" over time. Thus even if mass schooling elevated earlier cohort's fluid IQ, later cohorts were supposedly exposed to weaker cognitive enhancing environments that could not have been a cause of the continuation of the Flynn effect later into the century (e.g. Williams, 1998). But, first this assumption has never received empirical support, and second its premise is challenged by a recent analysis of the cognitive demand of American mathematics curriculum over the 20th Century as follows.

An analysis of over 28,000 pages from 141 elementary school mathematics texts published between 1900 and 2000, undertaken by Baker et al. (2010a), finds that

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[5] Raven's progressive matrices are non-verbal multiple-choice measures of the reasoning, where for each test item the subject is asked to identify the missing element that completes a pattern with varying dimensions of shading, shape, and spacing.

widely used mathematics textbooks by the mid-1960s contained several notable changes:(1) an expansion of topics and the number of pages devoted to each topic; (2) traditionally more advanced topics were shifted from higher to lower grades; and (3) the cognitive demand of instructional materials, in terms of the abstraction and conceptualization of fluid problem-solving strategies, increased significantly from Kindergarten to 6th grade. Over the last several decades, students are increasingly asked to learn content that engages them in activities such as estimation and developing multiple solution strategies for problems that demand effortful cognitive skills closely associated with executive functioning (Bull and Scerif, 2001; Espy et al., 2004). Also, similar findings of the growing cognitive demand of the reading curriculum since the late 1960s have recently been presented (Stevens et al., 2011).

This is not to suggest that fluid IQ increases have made for later generations mostly made up of individuals with superior general intelligence or that past generations were composed of many with severely low intelligence. Rather, the Flynn effect likely reflects the population expression of exposing many individuals to the schooling environment that assists in developing genetically endowed neurocognitive capacity (e.g. Martinez, 2000).

Lastly, there are two telling examples of how the neurocognitive impact of the education revolution influences other social institutions. The first is the change in job content over the second half of the last century across the American occupational structure. A time series analysis of job content changes across a consistent set of 264 occupations and 64 industries from the 1960 to 1985 finds as non-cognitive skills have dropped, the substantive complexity of jobs requiring analytical reasoning (i.e. combinations of mathematics, language and reasoning skills) and synthetic reasoning (i.e. putting different ideas and concepts together in new ways, effortful thinking, and new problem-solving) have increased significantly (Howell and Wolff, 1991). While certainly some of these changes are due to technology, the second example indicates that a cognitively enhanced workforce changes business strategies of firms and can have significant impact on economies. In this case, much research has shown that technology complements the worker with more general cognitive skill and makes employing them more profitable through what labor economics refer to as 'pervasive skill-biased' (read, pervasive educated-biased) technology (e.g. Autor et al., 1998; Berman et al., 1998; Dom et al., 1997; Murname and Levy, 1996). The use of pervasive skill-biased technology, which is compatible with greater cognitive abilities, increased over the course of the education revolution in the US, and has been shown in macro-statistical models to be a causal agent of economic growth over the 20th Century (e.g. Goldin and Katz, 2008).

2. Cognitive neuroscience of the schooling effect

The influence of the robust culture of cognition throughout society is in part attributable to the fact that social status, and all that it implies for one's life, is now heavily determined by academic achievement and attainment. And while this is a sociological argument about what gives formal education its deep meaning in society, it has nothing to say about causal mechanisms that underlie the micro-cognitive and behavioral effects of exposing human populations to schooling's systematic cognitive stimulation, organizational framework, assessment methods and social institutional values that have lasting effects across the lifespan. An important foundational premise to clarify in the education-neuroscience discussion is that cognitive development is a universal property of normal brain maturation and occurs irrespective of schooling and varied cultural-linguistic factors. That is, the natural course of human neurocognitive development is to acquire language, skills, and knowledge that are beneficial to survival, reproduction and continued adaptation to one's environment.

Neuroscience research has confirmed that this occurs even in circumstances of severe environmental impoverishment and several forms of early brain pathology (e.g., Chugani et al., 2001; Eslinger et al., 2004; Senghas et al., 2004; Vargha-Khadem et al., 1997). The neurobiological plasticity underlying human cognitive development is robust enough to thrive despite many biological and environmental hazards, but at the same time, there is increasing evidence that such development is invariably tethered to one's immediate environment and shapes the brain in specific ways. Social, cultural and other environmental exposures and demands, in a sense, are mediating and constraining variables that influence neurocognitive maturation. Therefore, it seems reasonable to propose that mass schooling has evolved in part to align with this natural developmental neurocognitive cascade that shapes the age when formal schooling can begin, the types of instruction and domain content, the gradually increasing complexity of the curriculum and expected independence of the learner, and the widening choices and options for advanced education.

The challenge, therefore, is to identify what the education revolution and its chief institutional product of mass schooling has added to the maturation and functioning of the cognitive brain and perhaps more importantly, what schooling can potentially add in future generations. For example, research has explored the assumption that executive function abilities influence the learning of academic topics such as mathematics, but the implications of the aforementioned research on schooling effects suggests that prior learning of literacy and numeracy may just as strongly influence the fluid IQ potential of the nervous system (Blair et al., 2005; Baker et al., 2010b).

There are three lines of neuroscience evidence we highlight that bear upon schooling effects on the brain. The first underscores the central role and fundamental importance of neural plasticity in the wide range of learning and adaptive human behavior. The second focuses on specific effects of schooling across samples of literate versus illiterates who did not have any schooling exposure due to social reasons. The third line of evidence derives from the study of learning in typically-developing, schooled children and adolescents.

2.1. Fundamental importance and central role of neural plasticity

Unlike, for example, a human hand that is formed *in utero* into its final shape and develops only through growth and strengthening, the brain of primates, including humans, is not close to a final structure upon birth. The postnatal brain with its huge initial number of synapses, potential for plasticity and propensities for learning, is biologically primed for "exuberance and pruning" (O'Leary, 1992). The former refers to an overabundance of possible connections and the latter, synaptic pruning, refers to the processes by which connections are strengthened and elaborated in complex network arrays through use and reinforcement (chiefly in the socially rich interactions of everyday life) and others are competitively pruned. Although the biological events may entail increased myelination of axons, a rise in local cerebral metabolic rate for glucose utilization, and electrophysiological changes in coherence patterns due to phase synchrony of spatially disparate regions among other processes, these may be functionally related to effects of environmental exposure and functional use (i.e., activity-dependent neural plasticity) (e.g., Hubel and Wiesel, 1962; Sperry et al., 1969; Quartz and Sejnowski, 1997). A fundamental link between education and brain plasticity can be surmised from the literature regarding specific training effects (or skill acquisition) on the brain. This approach can also be viewed as operationalized paradigms for evaluating activity dependent plasticity. Sources of observation have varied widely and included musicians, taxi drivers, jugglers, exercisers, whole body balancers, and medical students (e.g., Maguire et al., 2000, 2006; Draganski et al., 2004, 2006; Taubert et al., 2010). These revelations support several important implications for education, as follows:

- First, the plasticity effects were detectable in specific regions of the brain, such as the hippocampus of London taxi drivers trained in that city's spatial layout, the motion and spatial-sensitive areas of the occipital–parietal regions in jugglers, motor and auditory regions in musicians, and supplementary motor areas in whole body balancers. Hence, targeted training and skill acquisition can be associated with neural changes that are specific to those stimulus and task demands and may not generalize to other areas.
- At least some of the brain effects of training can be detected relatively quickly but little is known about what differentiates transient vs. long-term neural changes. For example, jugglers who acquired their skills and concomitant anatomical changes over 3 months were then restricted from juggling for 3 months. Both juggling expertise and percent grey matter change subsequently receded nearly but not completely to baseline (Draganski et al., 2004). However, medical students who were scanned 3 months before a major exam, a day or two after the exam, and then once more 3 months later, showed a more sustained pattern of neural plasticity. Expansion in the hippocampal region continued throughout the 3 time points wheras grey matter volume in the posterior parietal region increased throughout the intensive study period and then sustained it changes 3 months later. The more consistent neural changes in the medical students may have been due to the continued utilization of the extended learning. Hence, prompting progressive brain changes through compliance with intensive environment demands may be a process that also requires refresh mechanisms to maintain long-term cognitive and neural gains.
- Finally, the role of neurocognitive and learning factors in fostering brain changes from training effects is likely to be considerable. For example, individuals with various forms of learning disability and other neurodevelopmental conditions may require quite different parameters of training in order to foster brain plasticity effects (e.g., Butterworth et al., 2011). Conversely, others may learn unusually quickly or in styles that prefer one modality more than another. More broadly, there are likely to be important motivational and cognitive constraints and contributors to training effectiveness that may have some originating bases in neural architecture.

2.2. Specific neural effects of schooling in literates vs. illiterates

There is increasing evidence that schooling effects may be mediated in part by neural plasticity. Functional brain imaging studies comparing illiterate and literate adults confirm that there are different brain activation patterns recruited during language-mediated tasks. The illiterate adult group, carefully recruited from a small village in southern Portugal, was from the same families and sociocultural background as the literate group but unable to attend school due to family obligations (e.g., eldest daughter who took care of younger siblings who did attend school). All participants were socially and functionally normal and performed within the normal range on measures of oral naming and identification of real objects, body part naming, phrase comprehension, repetition of words and phrases, verbal fluency, limb praxis, general knowledge and episodic memory (Castro-Caldas et al., 1998). PET imaging occurred during real word and pseudoword repetition tasks. Contrast of real versus pseudoword repetition revealed that the literate adults activated the left posterior parietal region (Brodmann's area 40, angular gyrus) to a greater extent than illiterates. Lesser differences were detected in the left superior and middle frontal cortex (BA 8, 9), the left occipito-temporal region (BA 19, 37) and right parietal–occipital–temporal zone (BA 39, 37, 19). These differences occurred despite the fact that accuracy of repetition was fairly similar (98% for literates vs. 92% for illiterates). Illiterates, however, did not fare as well with pseudoword repetition (only 33% correct vs. 84% correct for literates), and activated much fewer regions than literates. Subsequently, Petersson et al. (2000) reported that network activation analysis of real word vs. pseudoword repetition showed clear differences between these tasks in the illiterate group but not in the literate group. The illiterate group used different connectional networks linking Broca's area and the inferior parietal lobule as well as in the region of the posterior midinsula bridge between Wernicke's and Brocas'a areas.

The two groups did not differ in brain regions recruited during real word repetition which was thought to represent a more natural language skill. Hence, training in sound-letter processing can reasonably be implicated as a contributor to functional changes in brain architecture.

Anatomical comparisons have similarly supported neural differences due to schooling exposure. Late literacy acquired in adulthood does not have the confounding developmental anatomical and physiological effects of maturation and hence can provide a relatively clean glimpse of brain changes related specifically to acquiring literacy. In late literates who had been reading and writing for at least 5 years, Carreiras et al. (2009) detected a larger splenium of the corpus callosum and greater grey matter volumes in the inferior parietal, dorsal occipital and middle temporal regions as well as the left supramarginal and superior temporal cortices – regions implicated in the typical circuitry underlying reading. The corpus callosum findings fit well with the data of Castro-Caldas et al. (1999) who detected that the white matter was significantly thinner in illiterates compared to literates in the anterior portion of the posterior third of the corpus callosum. This region is where crossing fibers interconnect the posterior temporal and parietal lobe regions associated with auditory and language processing. The functional connectivity analyses of Carreiras et al. (2009) revealed additional interactions associated with literacy, specifically increased connectivity of the left and right angular gyri and left angular gyrus modulation of activity involving the dorsal occipital and supramarginal gyri.

Related, in doing magnitude judgment tasks, functional brain activation differences have been identified in illiterates (Deloche et al., 1999). Illiterates reported using more visual mediation strategies, whereas literates described mainly abstraction strategies to solve the problems. Interestingly, the illiterates showed activations of the occipital and temporal lobes bilaterally whereas the literates recruited left hemisphere regions in the frontal, temporal and parietal lobes.

Ardila et al. (2010) have argued that formal schooling does not simply endow a person with certain knowledge but more broadly extends the breadth and depth of cognition beyond that specific knowledge to several derived capacities for interacting with the world in a vastly different ways. For example, reading (and more broadly literacy) is viewed as an additional instrument for acquiring information (such as from books, manuals and computers) that trains specific abilities (e.g., phonological awareness, grammar and syntax) and that fosters more formal cognitive operations such as conceptualization and interpretation. The social and cultural environment of schooling also reinforces the shared contexts of cognition and social interaction such as teacher–student and class learning, incremental learning, competitive assessment of learning and knowledge, and demonstration of progress/productivity that is likely to shape the neural modulation of self-other processing, future-oriented thinking, and self-awareness that continues life-long.

2.3. *Study of learning in typically-developing schooled children and adolescents*

A fundamental scientific question for an envisioned bridge between cognitive neuroscience research and educational application is: What is the specific developmental role and effect of schooling as part of the social environment of activity and stimulation of the brain?

Some evidence highlights that neurocognitive development occurs at least through late adolescence and is highly responsive to the kind of environmental stimulation that routinely occurs in formal education. Contrary to an older assumption that most neurodevelopment reaches adult-like levels by early adolescence, recent research using a variety of methodologies finds that the brain develops by continued interactions with the environment well into early adulthood, if not longer (Duncan et al., 1995; Eslinger et al., 2004; Shallice and Burgess, 1991; Waltz et al., 1999). Studies observing the patterns of brain activation in typically-developing children and adolescents performing tasks that are systematically performed in schools, like arithmetic, suggest clear brain maturational differences. For example, the brain structures and networks involved in arithmetic performance are relatively well established by imaging studies (Ischebeck et al., 2007; De Smedt et al., 2009; Supekar et al., 2009; Butterworth et al., 2011) and can be targeted for schooling effects. In a recent developmental fMRI study of typical 8–19 year olds, the younger students who did not readily know the answers generated activations in broader high-order attentional and executive function areas more so than older students who generated focal and constrained activations in the arithmetic network suggestive of well-learned knowledge (Knipe et al., 2007). A study with results of similar implications was conducted by Ischebeck et al. (2007) exploring the effects of arithmetic training on brain activity. Specifically, arithmetic training decreased brain activation in the fronto-parietal regions and the caudate nucleus and increased activations in temporo-parietal areas such as the left angular gyrus. These findings supported a shift, after academic training, from the attention and executive processing-rich areas of the fronto-parietal regions to the more automatic and efficient knowledge retrieval areas of the temporo-parietal regions. That is, the study confirmed that specific academic training can significantly affect patterns of brain activity and, by extension, expertise in the targeted cognitive domain.

Lastly, education-related effects on brain architecture can be detected in pre-school children 4–5 years of age (James, 2010). When employing age-appropriate sensorimotor learning techniques such as letter printing vs. letter recognition training, enhanced BOLD activations were subsequently detected in visual association cortex during letter recognition testing in the letter printing group vs. the letter visual training group. Concordant ERP and fMRI data have supported the emergence of left occipito-temporal sensitivity to print letters as young (6 years old) student begin to acquire letter–sound associations (Brem et al., 2010). Hence, the call for an “educational neuroscience” approach to these issues of enhanced, normal and altered learning and neurocognitive development continues to gain traction and empirical support (e.g., McCandliss, 2010).

2.4. *Towards a dynamic bridge*

Considered together, the two clusters of findings point to a profound symbiotic relationship across the individual, institutional, and societal levels that influences and shapes neurocognitive development. What happens in classrooms around the world enhances not only the breadth and depth of specific content knowledge but perhaps more importantly the very nature of cognitive processing and especially the individual's executive functioning and high order cognitive capacities. Formal education enmeshes individuals in a uniquely different cognitive process in comparison to that related to subsistence level farming, early industrial factory work, and other pre-modern activities. With the exception of sacred and magical beliefs, anthropologically-speaking, the large mass of non-elite people over most of the course of human society probably have lived in a very concrete world linked to their immediate needs and environment.

The education revolution has spread a similar model of schooling widely and produced compelling motivation for ever-greater participation in this neurocognitive developmental environment of formal education. At the same time, education as a major social institution legitimates cognitive abilities as a key human capacity, and this idea has been integrated into many other institutions in contemporary society. For example, the emerging emphasis on continuing education, vocational retraining, and lifelong learning in adults are increasingly carrying many of the formal schooling concepts and expectations across the lifespan. In turn, the growing societal emphasis on cognition encourages the educational establishment to intensify the cognitive focus of curricula and teaching approaches. Lastly, a greater emphasis on executive functioning and higher-order cognition in schooling likely enhances the long-term developmental impact of education. This self-reinforcing cycle has probably been in place for some time, and will likely continue into the future (Baker, 2011a).

A dynamic perspective on a bridge between neuroscience and education as a neurocognitive developmental institution offers a number of potential avenues for future research. There are possibilities in both directions. For example, although there is growing research on how prior neurocognitive development assists in learning of academic material, the reverse process has been less examined. There is a need for more research on what it is about prior learning of basic literacy and numeracy skills that can enhance subsequent executive functioning and higher order cognitive abilities. Such discovery enables not only understanding of contemporary social changes, but also just as importantly the effective prevention of many diseases and causes of disability around the world. So too, little is known about the neurocognitive costs and benefits of what to teach, when to teach and how to teach different subjects, e.g., mathematics versus reading versus creative arts. Does learning how to read (and eventually reading to learn) render separate enhancements from those gained from learning number sense and arithmetic? Do different teaching approaches and curricular context increase the schooling effect on neurocognitive development, particularly the potential enhancement of executive functions and fluid IQ capabilities? How long into formal education does an enhancement occur and what is the nature of the effect over the school career, monotonically linear or not?

Similarly, social research on education has much to gain from a fuller appreciation of neuroscience. Even beyond their study of education, sociology and related fields have been slow to incorporate the findings of the cognitive revolution into their theoretical paradigms, and there is much to offer. Fearing reductionism and stuck in a radical rejection of all things biological, mostly sociology upholds an extreme version of nurture-only that now scientifically needs to be set aside. While it is true that society and its institutions are socially constructed, and has shown here these constructions can have significant impact on biological development, the nuanced perspective of an epigenetic world emerging from neuroscience is theoretically more robust and likely more predictive. For example, as reviewed above studying schooling as a social institution has opened up a greater empirical appreciation of the influence of education on society (Meyer, 1977). But even though this approach assumes a fundamental cognitive process at the heart of the construction of institutions, sociology has yet to test these assumptions with the findings and techniques of neuroscience. Such an undertaking would be beneficial to a greater integration of both fields.

Taken together, there is space to envision a new brain-mind-education 'bridge' embedded in the hypothesis of a powerful symbiotic relationship between the social institution of schooling and widespread enhanced cognition and brain maturation among populations. At this intersection, insights from evolutionary biology and developmental cognitive neuroscience meet with the historical emergence and nature of modern society and its main and distinctive social institutions. Although many of these new environments and forces have been unknown in previous historical periods, they quickly have become fundamental and stable social environments, introducing the kinds of sustained stimulation and demands that normal human beings today receive during their key developmental periods of life. The intertwined social and cognitive environment provided by these institutions – especially formal education – have increasingly come to be viewed as fundamental to the biological "hardware" of the brain for the very constitution and emergence of human consciousness and language as a new evolutionary phenomenon. The *cognitive revolution* might then be conceptualized more aptly as the *social neurocognitive* revolution, which has only just begun, and in which the education revolution is playing a significant role.

Conflict of interest statement

None.

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