

Children's Language Production: How Cognitive Neuroscience & Industrial Engineering Can Inform Public Education Policy and Practice

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Abstract

Little of 150 years of research in Cognitive Neurosciences, Human Factors, and the mathematics of Production Management have found their way into educational policy and certainly not into the classroom or in the production of educational materials in any meaningful or practical fashion. Whilst more mundane concepts of timing, sequencing, spatial organisation, and Gestalt principles of perception are well known and applied, the nature of Receiver Operating Characteristics (ROC) and the responsibility of the sender in that regard, as well as the maintenance of simplistic notions of developmental brain organization and hemisphericity for language rather than the neurophysiology of embodied language as an example, still inform pre-K-3 curriculum.

The paper intends to overview the science of human physiologic efficiencies in engineering terms in an attempt to develop novel approaches and thinking to classroom-based practice and subsequently leadership and policy informed by current neuroscientific realities and by production management and optimization principles now applied to schools, and their consumers.

Introduction

Recent spectacular advances in neurosciences have stimulated the hope that the application of our understanding that it is no longer about cerebral asymmetries and simplistic left-right differences but more complex applications of networks, and communication system principles that have led to newly developed concepts and findings that have not, as yet, found their way into educational practice and policy. We are at the cusp of developing breakthrough concepts in the understanding of educational processes, notably learning, memory, motivation and of course evaluation methods that examine these functions. Gradually it is being appreciated that there is considerable overlap between the problems of educational, sociological, and psychological processes and those of neurobiology, biochemistry and neurophysiology, and there is every possibility of reciprocal assistance. Researchers in these fields are willing to approach complex functions such as memory and learning on a physiological basis. We believe that the techniques and knowledge of neuroscience as well as Human Factors and Industrial Engineering notions of efficiency and production management can provide a service to education at all stages throughout life. There are findings of relevance for educators from those in the most diverse

biological fields. Although the human brain—the most crucial part of the anatomy—is the most complex mechanism known to man, it is now being analyzed in ways that are clearly significant for education. Recent research on the human brain has provided data relevant to understanding the processes of human learning and therefore to improving methods of teaching.

Education has been grabbing at straws for a long time. Often when a preliminary finding is reported in the neuroscience literature or presented at a conference it is grabbed and expounded upon with little consideration of the fundamental nature of biological process. For better or worse, over the last 10 years, education has been actively and aggressively looking to the biological sciences in order to inform education policy and practice. A good example is that of the 1998 decision in Georgia to fund an expensive program, to provide CDs of Mozart's music to all new mothers. In establishing this policy, the governor of Georgia drew heavily on work in cognitive neuroscience conducted at the University of California, Irvine. The actions were taken in the hope of "harnessing the 'Mozart effect' for Georgia's newborns—that is, playing classical music to spur brain development." Despite what the program implied, Mozart effect research, upon close examination, had little to offer education. One study, reported in *Nature* (Rauscher et al., 1993), found that listening to Mozart raised the IQs of college students for a brief period of time. Another study found that keyboard music lessons boosted the spatial skills of three-year-olds (Schlaug et al., 2005). Cognitive neuroscientists responsible for this work were baffled by Georgia's program and actions based on their work. Since this debacle, major figures in the sciences have published articles emphasizing caution and care as scientists, educators, and practitioners proceed down this exciting, but pitfall-laden road. These cautionary articles have laid the groundwork for relationships between neuroscience and education. However, there is a paucity of publications that systematically examine an area of research where conservative but confident claims can be made of the benefits of interdisciplinary.

Most currently prevailing patterns of education are heavily biased to wards left cerebral functioning and are antithetical to right cerebral functioning. Reading, writing and arithmetic are all logical linear processes, and for most of us are fed into the brain through our right hand. Most educational policies have tended to aggravate and prolong this one-sidedness. There is a kind of damping down of fantasy, imagination, clever guessing, and visualization in the interests of rote-learning, reading and writing, and arithmetic. Great emphasis is placed upon being able to say what one has on one's mind clearly and precisely the first time. The atmosphere emphasizes intra-verbal skills,"Using words to talk about words that refer to still other words" (Bruner, 1971).

If there is any truth in the assertion that our culture stresses left hemisphere skills and discriminates against the right hemisphere, this is especially true of school systems. Our society's overemphasis on "propositionality" at the cost of "appositionality" does not only result in adjustment difficulties but also in a lopsided education for the entire student body. Our students are not being offered the education they require to understand the complex nature of the world and themselves, an education for the whole brain. Sperry wrote: Our education system and modern society generally (with its very heavy emphasis on communication and on early training

in the three R's) discriminates against one whole half of the brain. I refer, of course, to the nonverbal, non-mathematical, minor hemisphere, which we find has its own perceptual, mechanical and spatial mode of apprehension and reasoning. In our present school system, the attention given to the minor hemisphere of the brain is minimal compared with training lavished on the left, or major hemisphere (Sperry, 1975).

Educational institutions have placed a great premium on the verbal/numerical categories and have systematically eliminated those experiences that would assist young children's development of visualization, imagination and/or sensory/perceptual abilities. The over-analytic models so often presented to children in their textbooks emphasize linear thought processes and discourage intuitivity, analogical and metaphorical thinking. These factors of neural functioning among children have been left to modification by random environmental rather than systematic institutional means. Education which is predominantly abstract, verbal and bookish does not have enough place for raw, concrete, esthetic experience, especially of the subjective happenings inside oneself. Education imposes a structure of didactic instruction, right-wrong criteria, dominance of the logical-objective over the intuitive-subjective on the learning child so early in the course of emergent awareness of his world and of himself, that except in rare cases creative potential is inhibited, or at least diminished. (*cf.* Melillo & Leisman, 2009). This leads us to affirm that our system of education is one which leads to the underdevelopment of the right hemisphere. As a result of excessive emphasis on intellectualizing, verbalizing, analyzing and conceptualizing processes, 'curriculum' has become equated with mere 'understanding'. This imposes 'neurogenic limitation' and binds mental processes so tightly that they impede the perception of new data. In the words of Gazzaniga a long time ago (1975), curriculum is "inordinately skewed to reward only one part of the human brain leaving half an individual's potential unschooled." The traditional preoccupation with formal intellectual education effectively blocks the possibility for the students to recognize and cultivate creativity and transcendence. It has been the adaptation and by educators of applications of brain sciences into the classroom and the culture of dichotomies of the Behavioral Sciences over the past 150 years that have placed undo reliance by our educational systems on functional brain models that may be irrelevant at best and damaging at worst to children's classroom performance and its evaluation.

What emerges as the central proposition of this paper is that (A) the examination and study of regional cerebral differences in brain function as a way of explaining and evaluating the learning process within the educational system is a non-starter. (B) The evaluation of students by standardized aptitude and achievement tests is not sufficient although probably still necessary and (C) the educational systems would be better to examine student performance and teach towards "cognitive efficiency" rather than simply mastery v. non-mastery with methods that employ both psychophysics that examine person-environment interaction and mathematical means of examining optimization and the strategy used to get there as well as how far or close a student is functioning from a mathematically derived optimization regression line or, in fact, how quickly the learner is progressing in that direction. Educators, although perhaps not palatable to

conceive of early childhood education as such, are producing a product and production management techniques should be useful for evaluating not just the product but the process or “manufacture” of that product as well.

Brain Anatomy is Irrelevant to Educational Practice

We possess, especially as adults, but with children as well, a high degree of localization of function, but that is not enough to explain the capacity for plasticity, regeneration, spontaneous recovery, and optimization in neurological terms and certainly not in its translation into educational practice. On the other hand, educational gains are measured largely by achievement and also by aptitude testing. Achievement testing deals with educational gains and not necessarily with the concept of optimization, and aptitude testing again largely deals with the probability of success but does not give a comprehensive view of the tools skills, both physiological and cognitive, that would directly relate to that educational success that would be better measured psychophysically and through the tool skills of project management, in the same way that cognitive optimization of pilots or air traffic controllers might be measured or evaluated and that product evaluation might be achieved.

In attempting to understand why neuroanatomic conceptualization is a non-starter for educational practice it is important to understand that what we are really attempting to achieve both in educational practice as well as in understanding the neurological basis of cognitive development is not what brain area controls a given cognitive function, but how efficiently it is operating. Whilst not the scope of this paper to provide a detailed overview of this principle, the reader is invited to review these concepts more comprehensively elsewhere (Melillo & Leisman, 2009).

To illustrate how it is that localization has greater relevance Fig. 1(A) below presents a CT-Scan of the brain of Terry Schiavo whilst in a persistent vegetative state and 1(B) of a young lady of normal intelligence born with hydrocephalus where no significant anatomic difference is evidenced between the PVS patient and the normally functioning young lady, but clear functional differences are noted during language processing.



Figure 1: (A) CT of normal (l.) and that of the brain of Terry Schiavo (r.) when the latter was in Persistent Vegetative State. (B) CT of normally functioning teenager with congenital hydrocephalus and a CT similar to that of the patient. (C) Regional Cerebral Blood Flow image of individual in (B) while performing language-based cognitive tasks.

The concept of “cortical efficiency” (Ertl & Schafer, 1969; Grabner et al., 2003; Grabner et al., 2004; Gilchrist, 2011) implies that higher ability in a cognitive task is associated with more efficient neural processing and not necessarily which brain region is involved in that processing. Whereas intuitively, we would expect higher performance to correlate with more activity, for the cerebral cortex the contrary is the case. Higher performance in several tasks, including verbal (Parks et al., 1988), numeric, figural, and spatial reasoning (Lamm, 1999; Vitouch et al., 1997) are consistent with the reduced consumption of energy in several cortical areas. This phenomenon has also been studied with EEG techniques in different frequency bands. The amount of a background power (7.5–12.5 Hz) decreases during cognitive activity compared with a resting state. This decrease has been observed to correlate with higher performance in subjects with higher IQ scores (Grabner et al., 2004) or with higher performance after training, indicating a more efficient processing strategy for a cognitive task (Neubauer et al., 2004). Most of these studies come from the psychological literature, focusing mainly on the domain of intelligence but drawing relatively little attention to the investigation of task performance in second language learners or bilinguals.

In an EEG coherence study on second language (L2) processing/bilingualism, an extension of the “cortical efficiency” paradigm was examined. Coherence is the amount of shared activity between any two electrode pairs and taken over the entire scalp surface, gives an index of inter-regional communication effectiveness. The acquisition of an L2 is equivalent to the training of a cognitive-behavioral skill, and some individuals respond to this training more efficiently than others. If an L2 is acquired before a certain age or critical period, even native speaker proficiency is achieved easily (early bilingualism). If training starts later in life, the proficiency level achieved depends on the amount of training, exposure, and on some kind of “predisposition” or aptitude of the individual. Whereas, in general, L2 processing involves the same language-specific cortical areas (with left hemisphere preference) as native language (L1) processing (*cf.* review by Perani and Abutalebi, 2005), neuroimaging studies have repeatedly shown that lower L2 proficiency is correlated with more widespread cortical activity (Perani et al., 2003), tacitly in line with the “cortical efficiency” concept, but not explicitly investigating it.

Reiterer and colleagues (2005) applied this concept in studying late bilinguals/second language learners, comparing, with EEG recording techniques, the recruitment of cortical areas during L2 processing in two groups of individuals differing profoundly in L2 proficiency (although both had started to learn L2 at the same age). In using coherence analysis or the amount of sharing between any two wave trains and thus reflective of brain integration of functioning and efficiency, the coherence brain maps (exemplified in Fig. 2) revealed more pronounced and widespread increases in coherences in the $\alpha 1$ -band (8–10 Hz) in low-proficiency than in the high-proficiency L2 speakers. Surprisingly, this difference was obtained also during L1 processing and corroborated for both languages by multivariate permutation tests. These tests revealed additional differences between the low- and the high-proficiency group also for coherences within the $\beta 1$ - (13–18 Hz) and the $\beta 2$ -band (18.5–31.5 Hz).

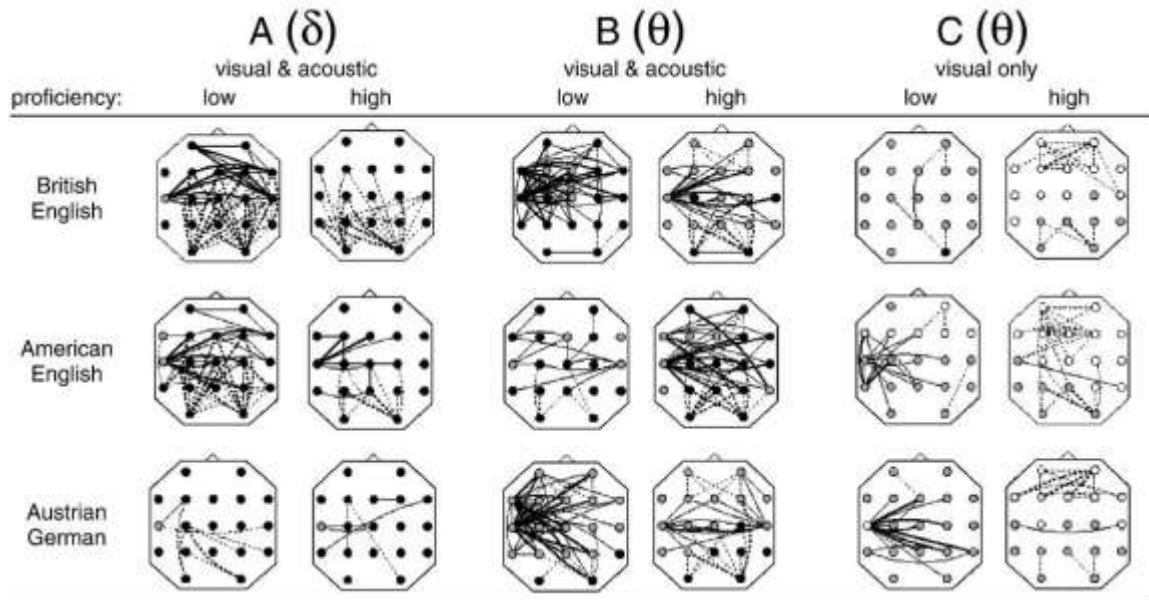


Figure 2: Coherence, or the amount of shared activity between EEG electrode sites, demonstrates significant coherence differences in high-proficiency versus low-proficiency bilinguals relative to the default condition (silence, noisy screen) in the δ frequency band (0.5–3.5 Hz) during processing of visual and acoustic signals (A), and in the θ -band (4.0–7.5 Hz), during processing of visual and acoustic signals (B), and of visual signals only (C). The text was either in British English (1st row), American English (2nd row), or in Austrian German (3rd row). (cf. Reiterer et al., 2005).

The point is that greater activity is demonstrated with less proficiency and vice versa. The function of childhood neurological development is precisely to facilitate the creation of localized function. This localization of function is not the explanation of a process, but rather the end-result of training. The efficiency of cognitive function is directly a consequence of the effectiveness of networks that now can be measured. Fewer brain regions necessary to accomplish a single task in one individual compared to another for the same task is a measure of efficiency. These networks active during learning and problem solving of all kinds are plastic and can be changed as a direct consequence of experience and training.

In attempting to apply Production Management concepts to child and adolescent neurocognitive performance to create a fundamental change in the educational training and evaluation paradigm, we can characterize the organization & development of large-scale brain networks using graph-theoretical metrics as represented in Fig. 3 below.

Figure 3

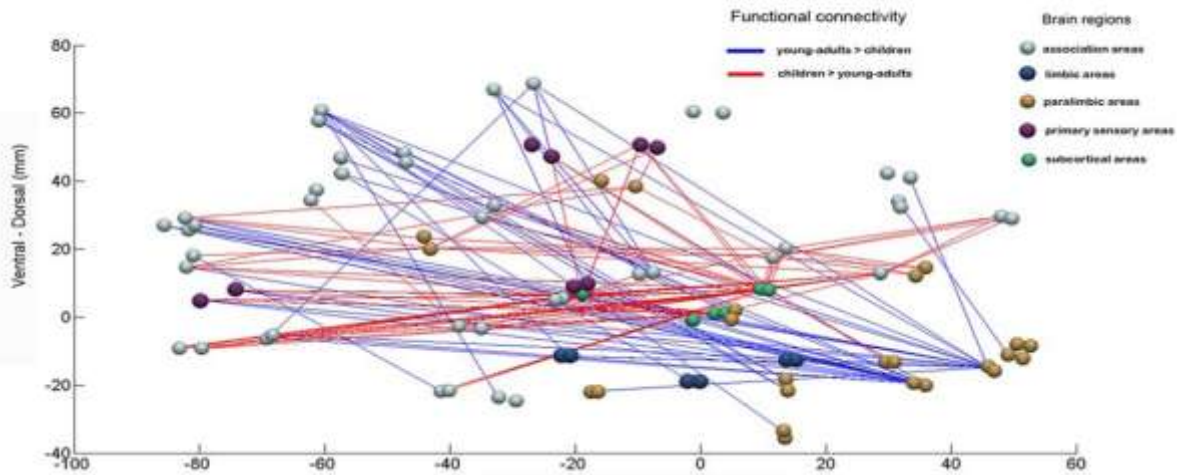


Figure 3: Functional connectivity along the posterior-anterior & ventral-dorsal axes showing increased subcortical connectivity (●), decreased paralimbic connectivity (●) in children, compared to young-adults. Brain regions plotted using y and z coordinates of centroids (in mm), 430 pairs of regions show increased correlations in children & 321 pairs showed significantly increased correlations in young-adults.

What we can learn from the characterization, organization and development of large-scale brain networks in children using graph-theoretical metrics is that small-world networks are characterized by an increased clustering coefficient or an average node-to-node distance (also known as average shortest path length) and a decreased characteristic path length (and represented in Figs. 4). Functional brain networks in children and young-adults show small-world properties. In mathematics, physics and sociology, a small-world network is a type of mathematical graph in which most nodes are not neighbors of one another, but most nodes can be reached from every other node by a small number of steps. Specifically, a small-world network is defined to be a network where the typical distance L between two randomly chosen nodes (the number of steps required) grows proportionally to the logarithm of the number of nodes N in the network, that is (Watts & Strogatz, 1998):

$$L \propto \log N$$

In the context of a social network, this results in the small world phenomenon of strangers being linked by a mutual acquaintance. Many empirical graphs are well-modeled by small-world networks. Social networks, the connectivity of the Internet, Wikipedia, and gene networks all exhibit small-world network characteristics.

These findings suggest sub-networks of densely connected nodes, connected by a short-path. Functional connectivity networks of brain from EEG (Leisman, 2011) as well and MEG (Stam, 2004) have also been shown to possess small-world architecture. Large-scale brain networks in 7-9-y-old children show similar small-world, functional organization. Functional brain networks in children show lower levels of hierarchical organization compared to young-adults. Children and young-adults possess different interregional connectivity patterns, stronger

subcortical-cortical connectivities in young adults and weaker cortico-cortical connectivities in children. Large-scale brain connectivity involves functional segregation and integration, stronger short-range connections in children, and stronger long-range connections in young-adults.

In taking this concept further, we note that represented in Figs. 4(a) and (b) below is a representation of functional connectivity along the posterior-anterior and ventral-dorsal axes showing elevated subcortical connectivity and decreased paralimbic connectivity in children, compared to young-adults. This clearly demonstrates that the wiring and connectivities of young children is significantly different that teenagers and beyond and the change in organization of these connectivities directly speaks to the issue of optimization of pathways and is a direct consequence of training and therefore of education. In attempting to apply graph theory to an understanding of language acquisition, Fig. 4(b) below shows the responses of both typically developing (TD) and of at-risk, late-talkers (LT). There is exists a significant and apparent visual difference in the networks with the TD's network showing higher clustering coefficient and higher median in-degree, but lower geodesic distance, than the LT. These differences are consistent at both the individual and population level.

Figure 4(a)

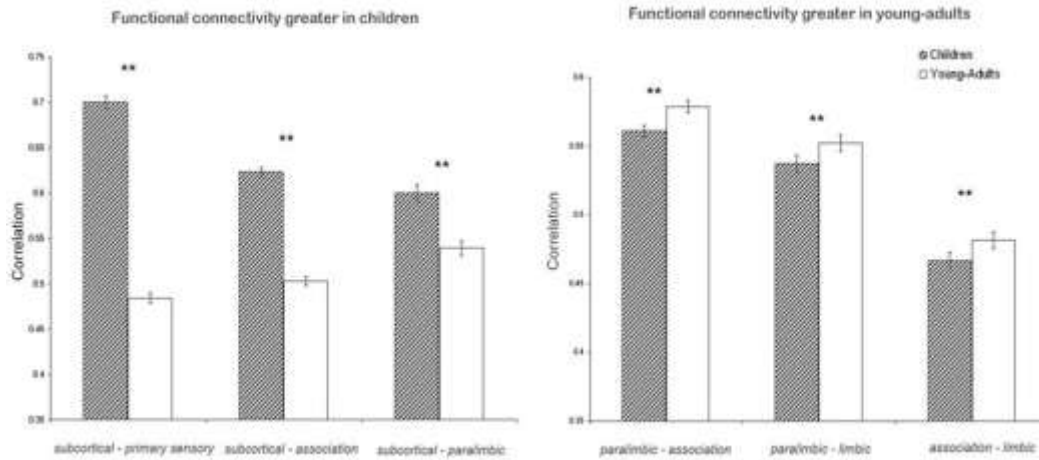


Figure 4(a) Characterization, Organization & Development of Large-Scale Brain Networks in Children Using Graph-Theoretical Metrics. (b) The graph on the left is a typically developing (TD) child (17 mo, 40%) and the graph on the right is of an at-risk, late-talker (LT) (24 mo, 10%). The network of the TD child includes the 60 words in the child's productive vocabulary and the network of the at-risk LT child includes the 61 words in the child's productive vocabulary. The apparent visual differences in the networks are supported by the differences in the corresponding table, with the typical talker's network showing higher clustering coefficient and higher median in-degree, but lower geodesic distance, than the LT. These differences are consistent at both the individual and population level.

Figure 4 (b)

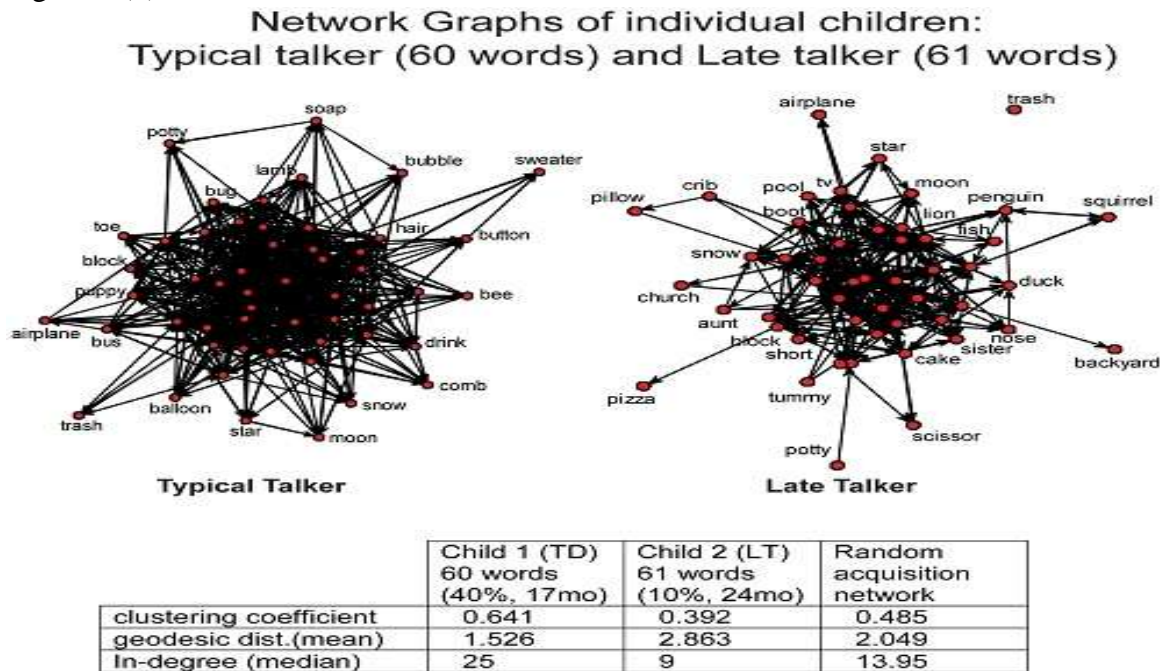
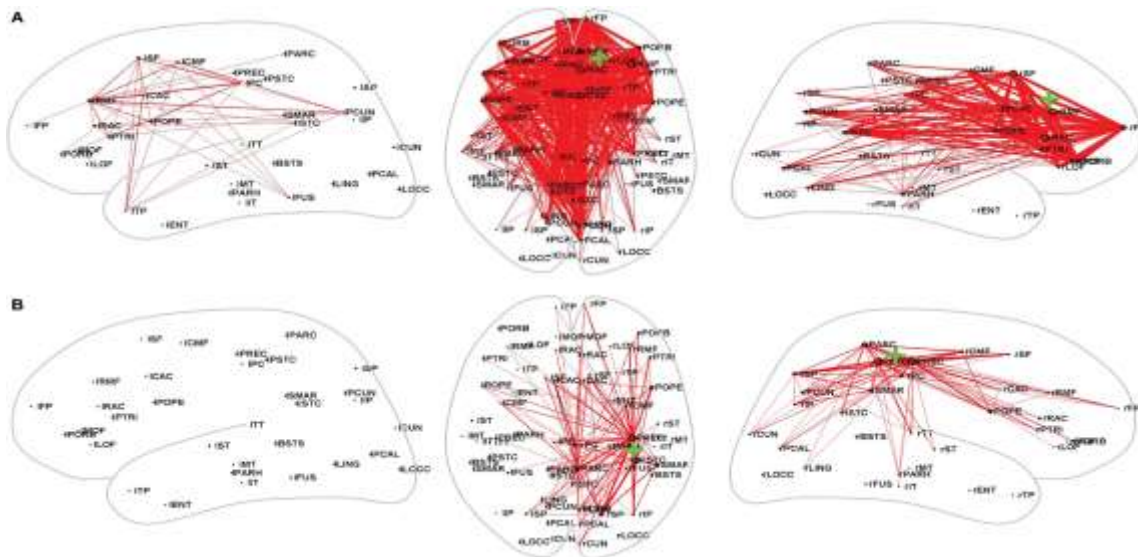


Fig. 5 demonstrates clearly the computational modulations in connectivity resulting from lesions in the (a) frontal cortex responsible for executive function, decisions, and therefore associations and (b) the sensorimotor cortex. Red lines indicate strength in connectivity. Note the widespread disruption caused by lesions in the prefrontal cortex compared with relatively constrained, intrahemispheric changes resulting from a lesion of the sensorimotor cortex.

Figure 5



Figures 5: Demonstration of computational modulations in connectivity resulting from lesions in the (a) frontal cortex and (b) sensorimotor cortex. Red lines indicate strength in connectivity. Note the widespread disruption caused by lesion in prefrontal cortex compared with relatively constrained, intrahemispheric changes resulting from a lesion of the sensorimotor cortex.

It has been thought since the time of both Broca and Wernicke that there exists a high degree of localization of function with an area anterior to the Sylvian fissure of the temporal lobes being responsible for expressive language and Wernicke’s area responsible for comprehension. Today we better understand that there no longer exists the localization of receptive functions in one area (*cf.* Fig 6(a)). Multiple stream models are more likely. Receptive language functions are organized into multiple self-organizing simultaneously active networks. It appears also as represented in Fig. 6 (b) that the meaning of words and sentences have been grounded indicating that there is an “embodiment” of meaning in brain networks as previously described.

Figure 6 (a)

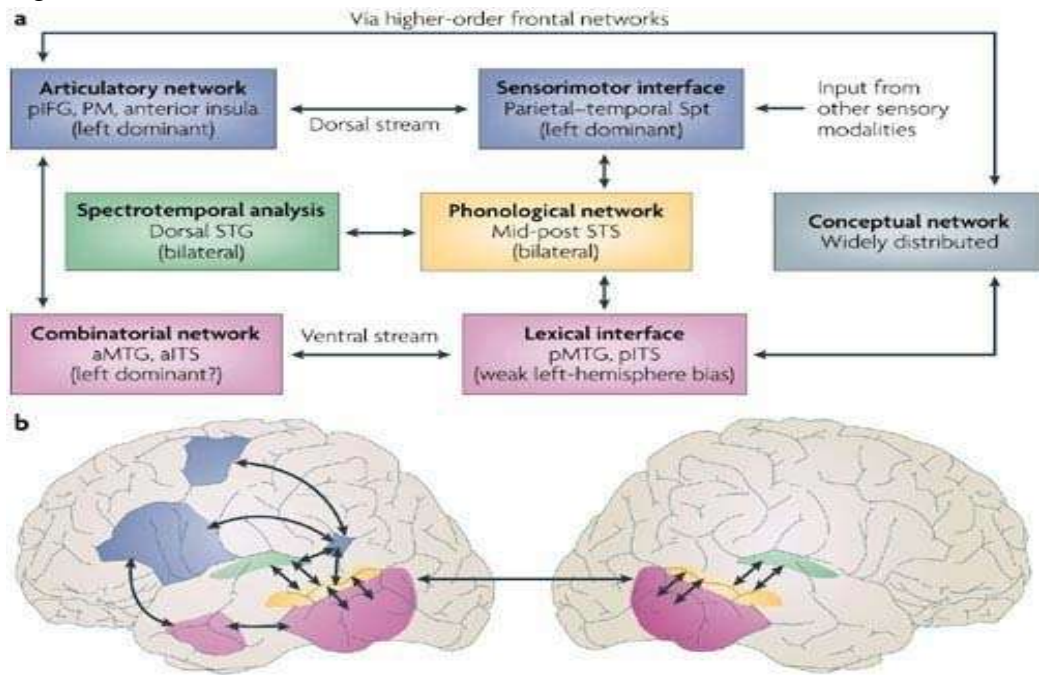
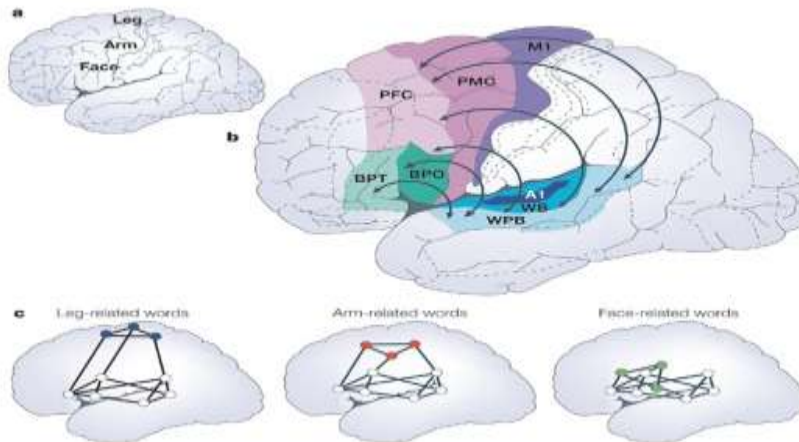


Figure 6 (b)



Figures 6: (a) Bye to the good old days: No more receptive functions in one (Wernicke's) area. Multiple stream models are more likely. Receptive language functions are organized into multiple self-organizing simultaneously active networks. (b) grounded meaning indicates that the meaning of words and sentences have been claimed to be "embodied"

Figure 7 (a)

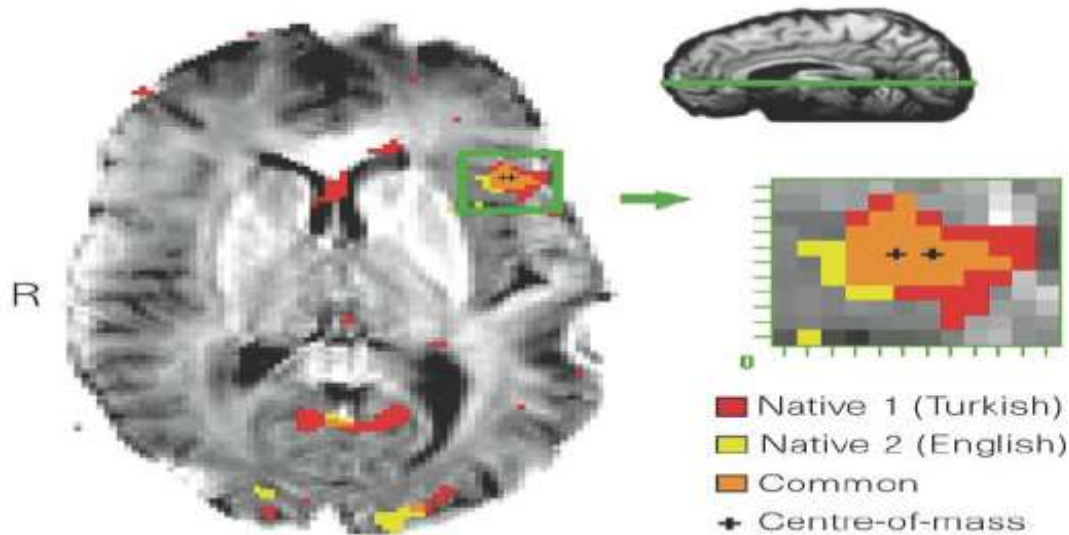
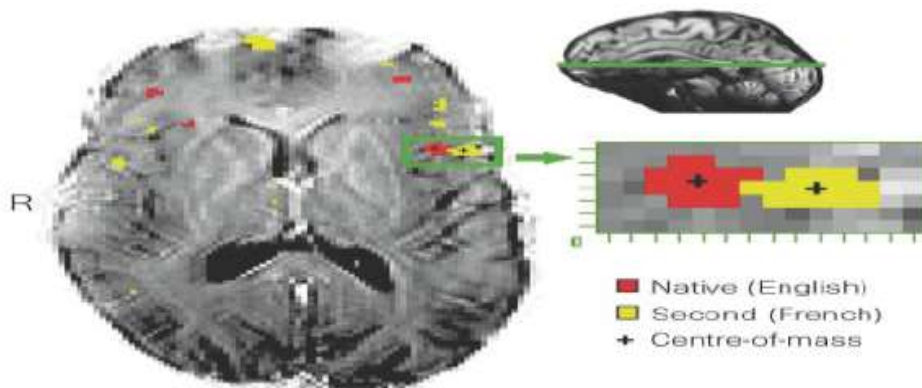


Figure 7(b)



Figures 7(A) and (B) represent the effect of brain on early as opposed to late exposure to a second language. The figures clearly indicate the nature of the optimization and efficiency of brain function connections when notions that related to early training and critical periods are applied.

DISCUSSION

The paper has attempted to overview the nature of neurologic processing efficiencies in engineering terms in an attempt to develop novel approaches and thinking to classroom-based practice and subsequently leadership and policy informed by current neuroscientific realities and by production management and optimization principles now applied to schools, and their consumers.

We have know that small-world networks are characterized by an increased clustering coefficient and a decreased characteristic path length. Applying this notion to brain networks in children, we note that functional brain networks in children and young-adults show small-world properties. This suggests sub-networks of densely connected nodes, connected by short path. The

functional connectivity networks of the brain from EEG-based systems demonstrate they possess small-world architecture. Large-scale brain networks in 7-9-y-old children show similar small-world, functional organization. Functional brain networks in children show lower levels of hierarchical organization compared to young-adults and children and young-adults have different interregional connectivity patterns, stronger subcortical-cortical connectivities in young adults and weaker cortico-cortical connectivity in children. Large-scale brain connectivity involves functional segregation and integration. Children possess stronger short-range connections as opposed to younger adults who demonstrate stronger long-range connections.

We have seen that brain connectivities are variously organized efficiently or inefficiently in systems that can be relatively easily measured. It is possible to evaluate optimized changes in brain connectivities after training and learning with applications ranging from progress in early child development, classroom instruction, and bilingualism. These brain connectivities are different and delayed in some as a direct consequence of experience. The measurement of skill and function based on grade level or binary considerations such as a child possesses or does not possess certain skills “medicalizes” the learning paradigm. The focus should be less on binary thinking and more on strategy and optimized performance most easily measured by processing speeds, and strategic solutions. For example individuals learning a second language late possess brain activity in regions that are not optimally coordinated and synchronized. As the brain continues to develop, more distant but simultaneously active areas require synchronization. It is the developmental lack of effective synchrony that we hypothesize speaks to the connections between motor and cognitive function and to the very nature of learning itself.

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